THRESHOLD

Interlaboratory Cooperative Study of the Precision and Accuracy of the Determination of

THE RELATIVE DENSITY OF BLACK SMOKE

(Ringelmann Method)

using

ASTM Method D 3211-73 T

DS 55-S10

AMERICAN SOCIETY FOR TESTING AND MATERIALS

Interlaboratory Cooperative Study | RELATIVE DENSITY OF BLACK SMOKE

05-055100-17

DS 55-S10

THRESHOLD

ASTM

FINAL REPORT

on

INTERLABORATORY COOPERATIVE STUDY OF THE PRECISION AND ACCURACY OF THE DETERMINATION OF THE RELATIVE DENSITY OF BLACK SMOKE (Ringelmann Method) USING ASTM METHOD D 3211-73 T

J. E. Howes, Jr., R. N. Pesut, and J. F. Foster

Battelle Memorial Institute

ASTM DATA SERIES PUBLICATION DS 55-S10

List Price $5.00

05-055100-17

ASTM **AMERICAN SOCIETY FOR TESTING AND MATERIALS**
1916 Race Street, Philadelphia, Pa. 19103

Library of Congress Catalog Card Number: 74-76293

NOTE

The Society is not responsible, as a body,
for the statements and opinions
advanced in this publication.

Battelle is not engaged in research for advertising, sales promotion, or publicity purposes, and this report may not be reproduced in full or in part for such purposes.

Printed in Gibbsboro, New Jersey

August 1974

TABLE OF CONTENTS

APPENDIX

LIST OF TABLES

(List of Tables Continued)

LIST OF FIGURES

(List of Figures Continued)

DS55S10-EB/Aug. 1974

INTERLABORATORY COOPERATIVE STUDY OF THE PRECISION AND ACCURACY OF THE DETERMINATION OF THE RELATIVE DENSITY OF BLACK SMOKE (RINGELMANN METHOD) USING ASTM METHOD D 3211-73T

by

J. E. Howes, Jr., R. N. Pesut, and J. F. Foster

INTRODUCTION

In 1971 in recognition of the important relationship between the measurement and the effective control of air pollution, American Society for Testing and Materials (ASTM) initiated a pioneering program, designated Project Threshold, to validate methods for measuring contaminants in the ambient atmosphere and in source emissions. The first phase of the program was devoted to evaluation of methods for measuring the content of nitrogen dioxide (D 1607-69), sulfur dioxide (D 2914-70T), dustfall (D 1739-70) total sulfation (D 2010-65), particulate matter (D 1704-61), and lead (D 3112) in the atmosphere[(1-5)*].

Methods for the measurement of the relative density of black smoke (D 3211-73T), oxides of nitrogen (D 1608-60), sulfur oxides (D 3226-73T), particulates (D 2928-71), and particulates and collected residue (proposed method) in source emissions have been evaluated in Phase 2 of Project Threshold. Evaluation of a pitot tube method (D 3154-72) for determining the average velocity in a duct and the condensation method for determining the moisture content of stack gases were also performed in conjunction with the particulates and collected residue tests.

The interlaboratory "round-robin" approach has been applied to Project Threshold by bringing together groups of competent laboratories for concurrent performance of the test procedures under actual field conditions. Each participating laboratory is responsible for providing personnel and equipment, assembling apparatus, sampling, and analyzing collected samples either on-site

*References are given on Page 40.

or at their own facility. The coordination of the testing program, statistical analysis of the data, and evaluation of the measurement methods based on the experimental results has been performed by Battelle's Columbus Laboratories.

This report presents the results obtained from an experimental study of the accuracy and precision of estimates of the relative density of black smoke using ASTM Method D 3211-73T (Ringelmann Method)[6].

SUMMARY OF RESULTS

A statistical analysis of Ringelmann number estimates of the density of black smoke from a generator and three sources made by seven certified smoke observers using the procedures described in ASTM Method D 3211-73T produced the following results:

- The average standard deviation, S_b, for variations among single black smoke density estimates by different observers (reproducibility) over the Ringelmann number range of 0 to 5 is expressed by the equation

$$S_b = 0.1 + 0.3 M - 0.07 M^2 ,$$

  where S_b and M, the mean smoke density, are given in Ringelmann numbers.
- There does not appear to be a significant difference between the reproducibility of observer estimates of generator-produced smoke plumes and emissions from actual sources.
- The overall mean of observer estimates of smoke density were less than the smoke generator transmissometer readings by about two percentage points, a difference which is statistically indistinguishable from zero. The observer-transmissometer difference showed no dependence on smoke density over the entire Ringelmann range.
- In general, observer estimates across the entire Ringelmann range were within 10 percentage points of generator readings. A significant bias was noted only at Ringelmann readings greater than 3-1/2.

EXPERIMENTAL PROGRAM

ASTM Test Method D 3211-73T

ASTM Method D 3211-73T is a subjective test which covers the determination of the relative density of black smoke by visual observation performed by a qualified, certified observer. The observer assigns a number to the density of a black smoke plume which in his judgement corresponds to a shade of gray on a Ringelmann Smoke Chart. The observer may make readings with the unaided eye, by direct comparison with Ringelmann Smoke Charts, or with the aid of a Smoke Scope[7]. The readings are taken at constant time intervals, within a specified distance from the stack, and at a specified location with respect to the plume and the sun.

A copy of ASTM Method D 3211-73T is reproduced in the Appendix of this report. The method includes additional discussion of conditions which may affect the density readings obtained in using the procedure.

Interlaboratory Test Procedure

The interlaboratory study of ASTM D 3211-73T consisted of six tests in which five to seven certified observers ~~estimated the density of~~ black smoke plumes from a smoke generator and three actual sources. All tests with the exception of Test 6 were conducted in accordance with the procedures prescribed by ASTM D 3211-73T. Test 6 (power plant smoke stack) deviated from the procedure in that observations were made at a distance of about 2500 meters from the source. The Test Method specifies that the observer stand no more than about 762 meters from the stack.

Tests 1, 2, and 3 were performed using smoke plumes of selected densities which were produced by an Environmental Industries generator[8]. Plumes of smoke densities ranging from 1/4 to 5 Ringelmann number were generated in random fashion based on values derived from a table of random numbers

Tests 1 and 3 consisted of 32 reading periods and 25 reading periods comprised Test 2. Approximately 45 to 90 seconds were required to change and stabilize the smoke density between readings. At each reading period a signal was given at which time all observers concurrently estimated smoke density. At the same time, the "standard value" of the smoke density was determined from the smoke generator transmissometer output. A calibration check of the transmissometer at 0 percent smoke density was performed periodically throughout the tests.

The observers began the test series without making any pretest smoke density observations. Between Tests 2 and 3, the observers were permitted to view 10 generator-produced smoke plumes of different densities, the Ringelmann numbers of which were announced to the observers.

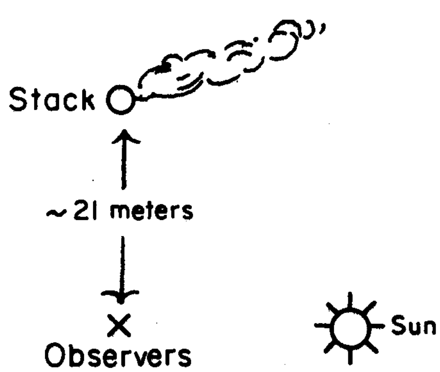
Full-sized Ringelmann Smoke Charts were available for use by all observers in Tests 1 through 3; however, all observers indicated that in accordance with their normal practice, smoke density estimates were made with the unaided eye.

Tests 4, 5, and 6 were performed using smoke emissions from boiler, coke plant, and power plant smokestacks, respectively. In each of these tests, all observers made concurrent smoke density estimates on signal at 30 second intervals. Each test consisted of 60 reading periods. All smoke density estimates in Tests 4 through 6 were made with the unaided eye; Ringelmann Smoke Charts were not used.

Test Site Conditions

Generator Tests 1, 2, and 3

Tests 1, 2, and 3 were performed at Wayne County's Eloise Health Department smoke generator facility located at Eloise, Michigan. The tests were conducted on June 7, 1973, from 8:30 a.m. to 10:45 a.m. EDST. The test conditions and relative positions of the observers, stack, and sun are given in Figure 1. Stack height was about five meters.

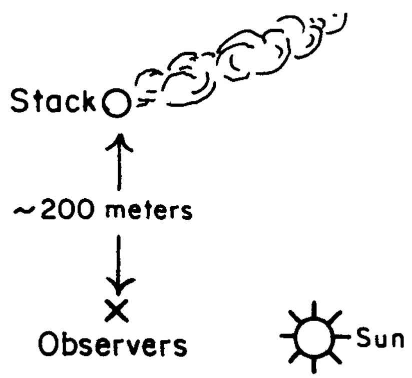


Sky - Clear, no clouds
Wind - WSW, 10 mph
Smoke readings each 45 to 90 seconds
Tests conducted 8:30 AM to 10:45 AM EDST

FIGURE 1. TEST 1, 2, AND 3 CONDITIONS FOR GENERATOR SMOKE READINGS

Boiler Stack, Test 4

The test was conducted on June 7, 1973 from 11:05 a.m. to 11:35 a.m. EDST. Test conditions and relative observer, stack, and sun positions are shown in Figure 2. Figure 3 gives the observers' view of the boiler stack and surroundings. Figure 4 shows the smoke emission. Height of the stack is approximately 30 meters.

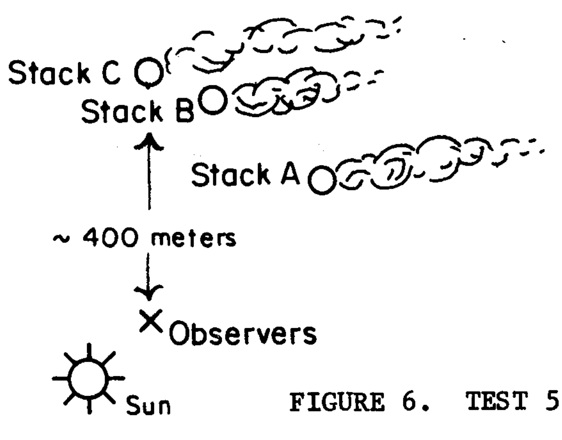


Sky - Clear, One cloud behind stack
Wind - West, 10-15 mph
Readings taken every 30 seconds
Test conducted 11:05 a.m. to 11:35 a.m. EDST

FIGURE 2. TEST 4 CONDITIONS FOR BOILER STACK SMOKE READINGS

Coke Plant Stacks, Test 5

Test 5 consisted of smoke density estimates of emissions from two of three coke oven stacks. Figure 5 shows the site from the area where smoke readings were taken. Figure 6 shows the relative locations of the stacks, observers, and the sun and other test conditions. The stacks designated A and C were used in the test. The test was performed on June 7, 1973 from 1:30 p.m. to 2:00 PM EDST. Stack heights are estimated to be about 50-60 meters.

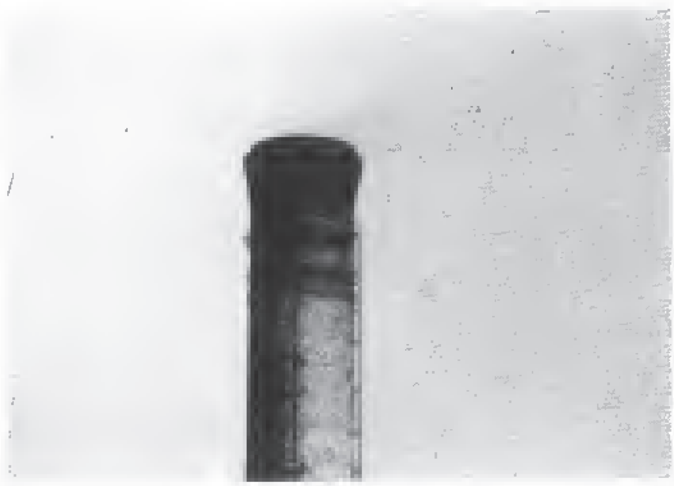


Sky - Clear
Wind - West, 20 mph
Reading taken every 30 seconds
Test conducted from 1:30 to 2:00 p.m. EDST

FIGURE 6. TEST 5 CONDITIONS FOR COKE PLANT STACK SMOKE READINGS

FIGURE 3. OBSERVER VIEW OF BOILER STACK USED FOR TEST 4 SMOKE READINGS

FIGURE 4. SMOKE PLUME FROM BOILER STACK USED FOR TEST 4 SMOKE READINGS



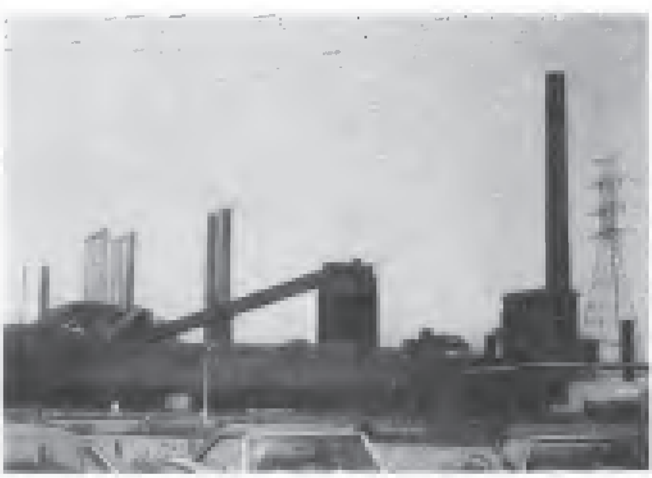
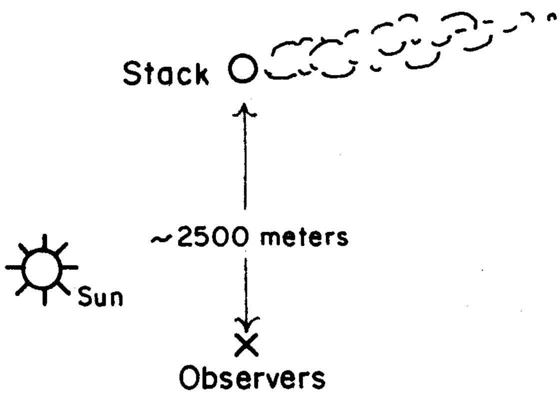


FIGURE 5. COKE-PLANT STACKS USED FOR TEST 5 SMOKE READINGS

Power Plant Stack, Test 6

Figure 7 gives the test conditions and the relative positions of the observers, stack, and sun during Test 6. The test was performed on June 7, 1973 from 2:30 to 3:00 p.m. EDST. As noted previously, smoke density estimates in this test were made beyond the maximum stack-observer distance specified in the Test Method. The estimated stack height is 60-70 meters.



Sky - Clear
Wind - West, 20-25 mph
Readings taken every 30 seconds
Test conducted from 2:30 to 3:00 p.m. EDST

FIGURE 7. TEST 6 CONDITIONS FOR POWER PLANT STACK SMOKE READINGS

Smoke Observer Participants

Seven certified observers participated in the smoke reading tests. The most recent certification dates of the observers ranged from about 2 to 11 months. The participants' smoke reading experience ranged from about 1 to 20 years with an average of 7 years. Four of the seven observers perform smoke observations on a more or less regular basis as part of their duties with state and county air pollution control organizations. Three observers are members of research organizations and do not perform smoke observations regularly. All observers had made smoke density estimates within two months prior to the test date.

The test participants were

Samual Gibbs	Wayne County (Michigan) Department of Health Air Pollution Control Division
Tom McCollough	George D. Clayton and Associates
James McReynolds	TRW, Research Resources, Inc.
Milo Smith	Michigan Department of Natural Resources Division of Air Pollution Control

James Tibbitts	Erie County (Pennsylvania) Health Department
Bernard Wagar	Wayne County (Michigan) Department of Health Air Pollution Control Division
Denny Wagoner	Research Triangle Institute .

Throughout the report, the identity of the participants is concealed by the use of letter code designations.

STATISTICAL ANALYSIS OF SMOKE DENSITY ESTIMATES

Statistical Measures

The evaluation of ASTM Method D 3211-73T for determining the relative density of black smoke was designed and conducted to study the following characteristics:

1. The observer-to-observer variability in estimating the relative density of black smoke
2. The effect of smoke density on the variability of Ringelmann number estimates
3. The presence of bias in the Test Method.

These characteristics are described in this report by the following statistical measures.

Reproducibility

Concurrent estimates of smoke density were made by five to seven observers. The differences among the estimates of smoke density represent a measure of variability between observers in application of the Test Method. The standard deviation of all smoke density estimates by all observers provides a measure of precision of the Test Method which is called "reproducibility" and is represented by the symbol S_b.

Accuracy

The observers estimated the Ringelmann numbers of plumes of known density produced by a smoke generator. Differences between the observer estimates and the smoke generator values is a measure of the accuracy of the Test Method. The average of the differences over the tests by all observers provides a measure of the bias of the Test Method.

Additional discussions of the preceding statistical measures are given by Mandel[9] and in ASTM publications[10,11].

Experimental Data

Six sets of data corresponding to results of the six tests were collected for evaluation of the procedure for determining the density of black smoke. The data are presented in Tables 1 through 6. Tables 1 through 3 present the data obtained from Tests 1, 2, and 3 in which the smoke generator was used. The use of the generator permitted the control of variations in smoke density across the full range of Ringelmann numbers so that the variability of the method could be studied in relation to the relative smoke density. Tables 4 through 6 present the data obtained from Tests 4, 5, and 6 with smoke emitted from a boiler stack, coke plant stacks, and a power plant stack, respectively. These tests using source smoke emissions permit the study of variability of the method under actual field conditions.

A total of seven observers participated in the tests. For tests 1, 2, and 3 with the smoke generator, only a subset of observers were used for each test as indicated in Tables 1 through 3. The tables show the observers' Ringelmann number estimates for each reading period. The last row of these tables shows the readings obtained from the generator transmissometer. These readings are taken as the "standard values" against which the readers' results are compared for the analyses of the accuracy of the Test Method.

All seven readers participated in Tests 4, 5, and 6 as shown in Tables 4 through 6. In these tests, Ringelmann number estimates less than one were noted, but no attempt was made to estimate the low readings to the nearest 1/4 Ringelmann number. In Test 6, a few readings greater than four were noted, but again no attempt was made to estimate the values to within 1/4 Ringelmann number.

TABLE 1. OBSERVER ESTIMATES AND SMOKE GENERATOR READINGS OF SMOKE DENSITY FOR TEST NO. 1

Observer	Reading Period[a] 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A	2-1/4	2	1-1/4	4	2-3/4	4-1/2	1-1/2	4	1	1-3/4	3-1/4	3/4	3	3-1/2	3/4	4-1/4
B	1-3/4	1-1/4	1/2	3-1/2	2-1/4	4-1/4	1-1/4	4-1/4	3/4	1-3/4	2-3/4	1-1/4	2-1/4	2-3/4	1	3-3/4
C	2-3/4	2-1/2	1	3-3/4	3	4-1/2	2-3/4	4-1/4	3/4	2	4	1-1/4	3	3-1/2	1-1/2	4-1/4
D	2	1-1/2	1	3	2-1/4	4	1-1/2	4	1-1/2	2	3-1/2	2	2-1/2	3-1/2	2	3-3/4
E	2-1/4	2	1	3-1/4	2-1/4	4-1/4	1-1/2	4-1/2	1/2	1	3-1/2	1-3/4	2-1/2	3-1/2	1-1/4	4
Smoke Generator[b]	2-1/4	1-3/4	3/4	3-1/2	2-1/2	4-1/2	1-3/4	4-3/4	3/4	1-1/2	3-1/2	1-1/2	3	3-3/4	1-1/4	4-1/4

Observer	Reading Period[a] 17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
A	3-3/4	2-3/4	3/4	3-1/2	2-1/4	1-3/4	3/4	4	3	1/4	1	3-1/4	4-1/4	1/4	3	2-1/4
B	3	2-1/4	3/4	3-1/2	1-3/4	1-1/2	1/2	4-1/4	2-1/2	1/4	1/2	2-1/2	4-1/4	1/4	2-1/2	1-3/4
C	3-1/2	3-3/4	2	4	2-3/4	2-1/2	1/2	4-1/4	3-1/2	1/2	1	3-1/2	4-1/2	1/2	3-1/4	3
D	3-1/4	3	2	4	2-1/2	2-1/4	1-1/2	4-1/4	3-1/2	1	1-1/2	2-1/2	4-1/4	1/2	2-3/4	2-1/2
E	3-1/2	2-1/2	1-1/4	3-3/4	1-1/2	1	1/2	4-1/4	2	1/4	3/4	2-1/2	4-3/4	1/4	2-1/2	1-1/2
Smoke Generator[b]	3-3/4	3	1-1/2	4	2	1-1/2	3/4	4-1/2	3	1/2	1	3-1/4	4-3/4	1/2	3-1/4	1-3/4

(a) Entries are Ringelmann number estimates.
(b) Based on smoke generator transmissometer reading.

TABLE 2. OBSERVER ESTIMATES AND SMOKE GENERATOR READINGS OF SMOKE DENSITY FOR TEST NO. 2

Observer	Reading Period[e]																															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
A	3-3/4	4	1/2	4	1-1/2	4	3-3/4	4	3-3/4	1-1/2	1/2	4	3-1/2	3	3-1/2	2-1/2	2	2-1/2	4	4-3/4	1/2	3-1/4	4	3	1-1/4							
B	3-3/4	3-3/4	1/2	3-1/2	2-1/4	4-1/4	3-1/2	3	2-1/2	1-3/4	1/2	4	2-1/2	2-3/4	1-3/4	1-3/4	1-1/4	2	2-3/4	5	1/2	1-3/4	2-3/4	1-3/4	1-1/4							
C	4-1/2	4-3/4	1	4-1/2	2-1/4	4-1/4	4	4	3-1/4	2	3/4	4-1/4	3-1/4	3-3/4	3-1/2	3-1/4	2	2-1/2	4	4-3/4	3/4	2-1/2	3-3/4	2-3/4	2							
D	4	4-1/2	1-1/2	4-3/4	2	4-1/4	4	3-1/2	3	2-1/4	1	4-1/2	3-1/4	3	2-1/2	2	1-1/2	1-3/4	4	4-3/4	3/4	1-3/4	2-1/2	2-1/4	1-3/4							
F	4-1/2	4-1/2	1/2	4-1/2	1-3/4	4-1/2	4-3/4	4	3	1-1/2	1/2	4-1/2	3-1/4	3	2-1/2	2-1/4	1-1/2	2	4-1/2	5	1/2	2-3/4	3-3/4	2	1-1/4							
Smoke Generator[b]	4-1/2	4-1/2	3/4	4-1/4	1-3/4	4-1/2	4-1/2	4-1/4	3-3/4	1-3/4	1/2	4-1/2	3-1/2	3-1/2	2-3/4	2-1/2	1-1/2	2-1/4	4-1/2	5	1/2	3-1/4	3-3/4	2-1/2	1-1/4							

(e) Entries are Ringelmann number estimates.
(b) Based on smoke generator transmissometer readings.

TABLE 3. OBSERVER ESTIMATES AND SMOKE GENERATOR READINGS OF SMOKE DENSITY FOR TEST NO. 3

Observer	Reading Period[a] 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A	4	3-3/4	3-1/2	1	5	1/2	1/2	3-1/4	3-1/2	3-3/4	2-1/4	0	2	4-1/4	1	2
B	3-3/4	3-1/2	2-3/4	1-1/2	5	3/4	1/2	2-3/4	3-1/2	4-1/4	2-3/4	0	2-1/2	4-1/4	1-3/4	2-3/4
C	4-1/2	3-3/4	3-1/4	3	5	1/2	3/4	3	3	3	3-1/4	0	3-1/4	4	2-1/2	2-3/4
D	4	3-1/2	2-1/2	1-3/4	5	1/2	1/2	2	2-3/4	3-3/4	2-1/4	1/2	2	4	2	2-1/2
E	4	4	3	1	5	1/2	3/4	1-3/4	2-1/2	3-3/4	1	1/4	1-3/4	4	3/4	1-3/4
G	4-1/4	4	3	2-3/4	5	3/4	1/2	2-1/2	3-1/4	3-3/4	1-3/4	1/4	2-1/2	4	2	2-3/4
Smoke Generetor[b]	4	3-1/2	3	1-1/2	5	1/2	1/2	1-3/4	2-1/2	4	1-3/4	1/4	1-3/4	4	1	1-3/4

Observer	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
A	3/4	3	3	3	1/2	2-3/4	1/2	4-3/4	1-1/4	3-1/4	1/2	1/4	1/2	2	1-1/4	3-1/2
B	2-1/2	4-1/4	3-1/2	4	2	3	1-1/4	4-1/2	2-1/2	3-3/4	1-1/4	1/4	1-1/2	3-1/4	2-1/4	4
C	2	3-1/4	3	3	1	3	3/4	4-1/4	2	3-1/4	1/2	1/4	1-3/4	3	2-1/2	3-1/2
D	1-1/2	3-1/4	2-3/4	3	1-3/4	2-1/4	3/4	4	1-3/4	3-1/2	1-1/4	1/2	3/4	2-3/4	2	4
E	3/4	3-1/4	2-1/2	3-1/4	1/2	1-3/4	1/4	4-1/2	1-1/4	3-1/2	1/2	0	1/2	2-1/4	1	3-3/4
G	1-3/4	3-1/2	3-1/4	3	1-1/2	2-1/2	1/2	4-1/2	2-3/4	3	3/4	1/4	1	2-1/4	2	3-3/4
Smoke Generetor[b]	1	3-1/4	2-1/2	3-1/4	3/4	1-3/4	1/2	4-1/2	1-1/2	3-1/4	3/4	1/4	1/2	2-1/4	1-1/4	3-1/2

(e) Entries are Ringelmann number estimates.
(b) Based on smoke generator transmissometer readings.

TA8LE 4. OBSERVER ESTIMATES OF THE OENSITY OF SMOKE FROM A BOILER SMOKESTACK (TEST NO. 4)

	Reading Period[(a)]																													
Observei	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
A	-	-	1	-	1-1/4	1	1	-	1	-	1	1	2	1-1/2	-	-	-	-	-	1	-	-	-	-	1-1/2	2	2	1	1-1/2	1-3/4
B	1-1/2	1-1/4	1	-	1	1-1/4	1-1/4	1	1-1/4	1	1 1/4	1-1/2	1-1/2	1-1/2	1	1	-	1	1-1/4	1-1/4	1	-	-	1	1-1/4	1-1/2	1-1/4	-	1	1
C	-	-	-	-	-	-	-	-	1	-	1	1-1/4	1-3/4	1-3/4	-	1	-	1	-	-	-	-	-	1	1-1/4	1-1/4	1-1/2	1	1-1/4	1 1/4
D	1	1	1	-	-	-	-	-	1	1	1	1	1-1/4	1-1/4	1	-	-	-	-	1	-	-	-	1	1-1/4	1-1/2	1-1/4	1	1-1/4	1-1/4
E	-	-	-	-	-	-	-	1-1/4	-	1	1	1-3/4	1-1/2	1	-	-	-	-	-	-	-	-	1-1/4	1-1/2	1-3/4	2	1-1/4	1-1/2	1-1/4	1-1/4
F	-	-	-	-	-	1	-	-	1	1	1	1-1/4	1-1/2	1-1/2	1	-	-	-	-	-	-	-	-	1	1-1/2	1-3/4	2	-	1-1/4	1-1/4
G	1	1	-	1	1	1-1/4	1	1	1	1-1/2	1	1-1/2	1-3/4	1-1/2	1-1/4	1	1	-	1	1	-	-	-	1-1/4	1-3/4	1-3/4	1-3/4	1-1/4	1-1/2	1-1/4

	Reading Period[(a)]																													
Observer	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
A	-	-	-	-	-	1	1	-	-	1	1-1/4	1-1/2	1	1	1-1/4	1-1/2	1	1	-	-	-	1	-	1	-	-	-	1	-	-
8	-	-	-	1	1	1-1/4	1	1	1	1-1/4	1-1/4	1-1/4	1-1/4	1-1/4	1	1-1/2	1	1	-	-	-	-	-	1	1	-	1	1-1/4	1	-
C	-	-	-	-	-	-	-	1	1	1	1	1	1	1-1/4	1	1-1/4	-	-	-	-	-	-	-	-	-	1	-	1-1/4	1	-
D	-	-	1	1	1	1	1	1	1	1	1-1/4	1-1/4	1-1/2	1-1/4	1-1/4	1-1/2	1	1	-	1	1	-	-	1	1	1	1	1-1/4	1	-
E	-	-	-	1	1	1-1/4	1	1	1	1	1	1	1	1	1	1-1/4	1	1	-	1	-	-	-	1	-	-	-	1-1/4	1	-
F	-	-	-	-	-	-	-	1	1	1	1	1-1/4	1-1/4	1	1	1-1/2	-	-	-	-	-	-	-	1	-	-	1	1-1/2	1	-
G	-	-	1	1	1	1	1	1	1	1-1/4	1-1/4	1-1/2	1-1/4	1-1/4	1-1/2	1-1/2	1-1/4	1	1	1	-	1	-	1	1	1	1	1-1/4	1-1/4	1

(a) Entries are Ringelmann numbers; - denotes Ringelmann number estimate is less than 1.

TABLE 5. OBSERVER ESTIMATES OF THE DENSITY DF SMOKE FROM COKE PLANT SMOKESTACKS (TEST NO. 5)

	Reading Period[a]																													
Observer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
A	3	2-1/2	2-1/2	2-1/2	2-1/2	2-1/2	2	1-1/2	1-1/2	1-1/2	-	1	-	-	-	2	1-3/4	1	1-1/2	1-1/2	1	1	1	1	1	1	-	-	-	-
B	3	2-1/2	2	1-3/4	1-3/4	1-3/4	2	1-3/4	1-3/4	1-1/4	1-1/4	1-1/4	1	-	1	1-1/4	1-3/4	1-1/2	1-3/4	1-3/4	1-3/4	1-1/2	1-1/4	1-1/4	1-3/4	1-1/2	1-1/4	1	1	1
C	2-1/4	2-1/4	2	2	2	2	1-3/4	1-3/4	1-1/4	1	1	1	1	-	-	1-3/4	1-1/2	-	1-1/2	1-1/2	1-1/4	1	1-1/4	1	1	1	-	-	-	-
D	2-1/4	2	2	2	2	2	2	1-1/2	1-1/2	1-1/4	1-1/4	1-1/4	1	1	-	2-1/4	2	1-1/2	1-1/2	1-1/2	1-1/2	1-1/4	1-1/4	1-1/4	1-1/2	1-1/2	1-1/2	1-1/4	1-1/4	1-1/2
E	3-1/4	2-3/4	2-1/2	2-1/4	2	2	1-3/4	1-1/2	1-1/4	1	-	-	-	-	2-1/4	1-3/4	-	2-1/4	2-1/4	1-3/4	1-1/4	1	1	1-1/4	1-1/4	1-1/4	1	1	-	1
F	2-1/2	2-1/2	2-1/2	2	2	2	2	2	1-1/2	1-1/4	1-1/4	1-1/4	1	-	-	1-1/2	1-1/2	-	1-1/2	1-1/2	1-1/4	1-1/4	1-1/4	1	1	-	1	1	-	-
G	2-1/4	2-1/4	2	2	1-3/4	1-3/4	1-3/4	1-1/2	1-1/2	1-1/4	1	1	1	-	-	1-1/4	1-1/4	1	1-1/4	1	1	-	-	1	1	1	-	-	-	-

	Reading Period[a]																													
Observer	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
A	1-1/4	-	-	-	-	-	-	1	-	-	-	-	2	1-1/2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	1-1/2	1-3/4	1-1/4	1	1	-	1-1/2	1-1/4	1-1/4	1-1/2	1-1/4	1	1-3/4	1-1/2	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C	-	-	-	-	-	-	-	-	-	-	-	-	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D	1-1/2	1-1/4	1	1	1	1-1/4	1-1/4	1-1/2	1-1/4	1	1-1/4	1-1/4	1-3/4	1-1/2	1	1	1	1	1	-	-	-	1	1	1	1-1/4	1	1-1/4	1-1/4	1-1/2
O	1	-	-	-	-	-	-	-	-	-	-	2-1/2	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	1	1	-
F	1	1-1/4	1	-	-	-	-	-	-	-	-	-	1-1/2	1	-	-	-	-	-	-	-	-	1	1	1	1	1	1	1	1
G	1	-	-	-	-	-	1	1	1	-	-	-	1-1/4	1-1/4	1	-	1	1	1	-	-	-	-	1	1	1	-	-	-	-

(a) Entries are Ringelmann numbers; - denotes a Ringelmann number estimate less than 1.

TABLE 6. OBSERVER ESTIMATES OF THE OENSITY OF SMOKE FROM A POWER PLANT SMOKESTACK (TEST NO. 6)

	Reading Period[(a)]																													
Observer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
A	1	1	1-1/2	1-1/2	2	2	2	2	2	2	2	2	2	2	2	4	+	4	4	3-3/4	3-1/2	3	3-3/4	3-1/2	3	3	3	3-1/2	3	3-1/2
B	1-1/2	1-1/4	1-1/4	1-3/4	2	2	2-1/4	2-1/4	2-1/2	2-1/4	2-1/4	2	2	1-3/4	2	2-1/2	3-3/4	3-3/4	3-1/2	3	2-3/4	2-1/2	2-1/2	2-1/2	2-1/4	2	2-1/4	2	2	2
C	1-3/4	1-3/4	2	2	2	2-1/4	2	2	2	2	2-1/4	2-1/4	2-1/4	2-1/4	2-1/2	3	3	3	3	3	2	2-1/4	2-1/4	2-1/4	2-1/2	2-1/2	2-1/2	2-1/2	2-1/4	2-1/4
D	1-3/4	1-1/2	1-1/2	1-1/2	1-3/4	1-3/4	1-1/2	1-1/2	1-1/2	1-1/2	1-1/2	1-1/2	1-1/2	1-3/4	1-3/4	2	3	3-1/2	3-1/2	3-1/4	3	3	3-1/4	3-1/2	3-1/4	3-1/4	3-1/2	3-1/4	3-1/4	3-1/4
E	2-1/4	2-1/4	2-1/2	2-1/2	2-1/2	2-1/2	2-1/2	2-1/2	2-3/4	2-3/4	2-1/2	2-3/4	2-1/4	2-1/2	2-1/2	3-1/4	4	4	3-3/4	3-3/4	3-1/2	3-3/4	3-3/4	3-3/4	3-3/4	3-3/4	3-3/4	3-1/4	3-1/4	3-1/2
F	—	—	—	—	2-1/2	2-1/2	2-1/2	2-3/4	2-3/4	2-3/4	2-3/4	2-3/4	2-3/4	2-3/4	3	3	3	3-1/4	3-1/2	3-1/2	3-1/2	3-1/4	3	3	3	3	3	3	3	3
G	1-3/4	1-1/2	1-1/2	1-1/2	1-3/4	1-1/2	1-1/2	1-1/2	1-1/2	1-1/2	1-1/2	1-1/4	1-1/2	1-1/2	1-3/4	1-3/4	2	2	2-1/2	3	2-1/2	2-3/4	2-3/4	2-1/2	2-1/2	3	3	3	3	2-3/4

	Reading Period[(a)]																													
Observer	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
A	3	4	2-3/4	2-1/2	3	4	+	4	4	3-3/4	3-3/4	2-1/2	4	4	4	3-3/4	3	3	4	4	4	3-3/4	3-1/2	3-1/2	3	2-1/2	2-1/2	3	3	3
B	1-3/4	2	1-3/4	1-3/4	2-1/4	2-1/2	3	3-1/4	3-1/4	3	2-3/4	1-3/4	3-1/2	3-1/4	3-1/4	2-1/4	2-1/2	2	3-1/4	3-1/2	3-1/4	3-1/4	3	2-1/2	2-1/4	2	2-1/4	2-1/4	2-1/4	2-1/4
C	2-1/4	2-1/4	2-1/4	2-1/4	2-1/2	2-1/2	2-3/4	2-3/4	2-3/4	2-3/4	1-3/4	1-3/4	2-3/4	2-1/2	2-1/2	2-1/2	2-1/2	2-1/2	2-3/4	2-3/4	3	3	3	3	2-1/2	2-1/2	2-1/2	2	2	2-1/2
D	3	3-1/4	2-3/4	2-1/2	2-3/4	3	3-1/4	3-1/2	3-1/2	3-1/4	2-1/2	2-1/2	3	3	3-1/4	2-3/4	2-1/2	3	3-1/2	3-1/2	3-3/4	3-1/2	3-1/2	3-1/4	2-1/2	2-1/4	2-1/4	2-1/4	2	2
E	3-3/4	4	3-1/2	2-1/2	3-1/4	3-3/4	4	4	3-3/4	3-1/2	3-3/4	4	4	3-3/4	2-1/4	3	2-3/4	3-3/4	4	4	3-3/4	3-3/4	3-3/4	3-1/2	2-1/2	2-1/4	2-1/4	2-1/4	2	2
F	3	3	3	3	3	3-1/2	3-1/2	3-1/2	3-1/2	3-1/4	3	2-1/4	3-1/2	3-1/2	3-1/2	3-1/2	3-1/2	3	3-3/4	3-1/2	3	3	3	2-1/2	2-1/2	2-1/2	2	2	2	2
G	3-1/4	3-1/4	3-1/4	3	3	3	3-1/4	3-1/2	3-1/4	3-1/4	3	3	2-1/2	3-1/2	3-1/4	3-1/4	3	2-3/4	2-3/4	3-1/4	3-1/2	3-1/2	3-1/4	3-1/2	3	3	2-3/4	2-1/2	2-1/4	2-1/4

(a) Entries are Ringelmann numbers; + denotes Ringelmann number estimate is greater than 4.

Preliminary Data Evaluation

A preliminary evaluation of the data from Tests 1, 2, and 3 was performed by examining deviations between reader estimates and generator smoke density readings using the procedures employed in smoke observer certification tests. In calculating the deviation, it is necessary to convert Ringelmann number readings to percentage smoke density as described in Paragraph 8.2 of the Test Method.

For each of the tests, the number of estimates which differed from the generator "standard value" by 20 percent smoke density or more (one or more Ringelmann number) were determined and the average deviations of the observer estimates from the generator values were calculated using the following equations:

$$\text{Average positive deviation} = \frac{\text{Sum of positive deviations}}{\text{Number of positive deviations}}$$

$$\text{Average negative deviation} = \frac{\text{Sum of negative deviations}}{\text{Number of negative deviations}}$$

$$\text{Overall average deviation} = \frac{(\text{Sum of positive deviations}) + (\text{Sum of negative deviations})}{\text{Total number of estimates}}$$

The summary of the deviation in the observer-generator smoke density readings is given in Table 7. Tests 1 and 2, which were conducted before allowing the observers to view smoke plumes of known density, show predominantly negative deviations in the reader estimates. Five observer estimates in Test 1 and 10 estimates in Test 2 deviated 20 percent or more in smoke density from the generator value. However, in Test 3, which was performed after the observers viewed smoke plumes of announced densities, 33 estimates deviate 20 percent smoke density or more from the "standard value" and the observer estimates exhibit predominantly positive deviations. It is obvious from the changes in the nature of the observer-generator deviations and in observer proficiency that the Test 3 data are significantly prejudiced presumably by the pretest smoke observations or by observer eye fatigue. Consequently, Test 3 data were excluded from the reproducibility and accuracy analyses and Test 1 and 2 data were used to determine these statistical characteristics.

TABLE 7. SUMMARY OF THE DEVIATION BETWEEN OBSERVER ESTIMATES AND SMOKE GENERATOR READINGS FOR TESTS 1, 2, AND 3[a]

Observer	Test 1				Test 2				Test 3			
	Number of Estimates[b] ±20% or more	Avg. Deviation in Estimates			Number of Estimates[b] ±20% or more	Avg. Deviation in Estimates			Number of Estimates[b] ±20% or more	Avg. Deviation in Estimates		
		+ (c)	- (c)	Overall		+ (c)	- (c)	Overall		+ (c)	- (c)	Overall
A	0	7.2 (9)	8.6 (14)	5.8	0	8.8 (4)	8.2 (14)	6.0	3	11.4 (11)	5.0 (10)	5.5
B	1	5.0 (1)	10.0 (27)	8.6	8	10.0 (1)	16.6 (19)	13.0	13	16.7 (23)	5.0 (3)	12.5
C	3	11.9 (16)	5.7 (7)	7.2	0	7.9 (14)	7.8 (9)	7.2	11	17.0 (20)	8.0 (5)	11.9
D	0	11.5 (13)	8.7 (15)	5.6	2	9.3 (7)	11.3 (15)	9.4	2	8.8 (21)	7.5 (4)	6.7
E	1	5.0 (3)	7.4 (25)	6.3	(d)	(b)	(b)	(b)	0	4.2 (4)	6.4 (11)	3.0
F	(d)	(d)	(d)	(d)	0	5.0 (2)	7.3 (11)	3.6	(d)	(d)	(d)	(d)
G	(d)	(d)	(d)	(d)	(d)	(d)	(d)	(d)	4	13.9 (18)	5.0 (3)	8.3
Totals & Averages	5	10.1 (42)	8.5 (88)	6.7	10	8.3 (28)	11.0 (68)	7.8	33	13.4 (97)	6.1 (36)	8.0

(a) Deviations are given in percent smoke density, 1 Ringelmann number = 20 percent density.
(b) Number of observer estimates which deviate 20 percent smoke density or more (1 or more Ringelmann number) from the smoke generator value.
(c) Numbers in parenthesis indicate the number of estimates with a positive or a negative deviation.
(d) Did not participate in test.

Reproducibility Analysis

Descriptive statistics for the test data shown in Tables 1 through 6 are presented in Tables 8 through 13. The top portion of these tables summarizes data across readers for each reading period (RDG.) within the test. These statistics include N, the number of observer estimates for each reading period; the mean, M; the standard deviation, S; the smoke generator transmissometer reading, SG, which is the standard to which the observer estimates are compared; the range (difference between highest and lowest value), w; an estimated standard deviation, SE; the ratio of range to estimated standard deviation, w/SE; and the coefficient of variation (100 S/M), CV, in percent. For Tables 11 through 13, standard values, SG, are not reported since these represent data collected in the field. The estimated standard deviations, SE, and ratio w/SE are not reported either, since the data for these tests were not used in the development of the reproducibility measure.

The statistics for each observer (RDR.) and the smoke generator (SG) for Test 1, 2, and 3 over the entire test are summarized at the bottom of Tables 8 through 13. In these tables N, M, and S denote for each test, the number of observer smoke density estimates, the mean of the observer estimates and the standard deviation of the observer estimates, respectively. These statistics reflect the variations introduced by the controlled changes of smoke density in the generator tests and the natural smoke density variations of the actual source emissions. The standard deviations are not directly related to the reproducibility of the Test Method.

The standard deviations (S) of the test data were calculated by the equation:

$$S = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{n-1}} ,$$

where $\bar{X}$ is the reading period or test mean, X_i is the smoke density estimate by the i^{th} observer, and n is the number of smoke density estimates per reading period or test.

TABLE 8. STATISTICAL ANALYSIS OF TEST 1 DATA

SUMMARY ACROSS READERS

TEST	RDG.	N	M	S	SG	W	SE	W/SE	CV
1	1	5	2.200	0.371	2.25	1.00	0.50	2.01	16.85
1	2	5	1.850	0.487	1.75	1.25	0.48	2.62	26.34
1	3	5	0.950	0.274	0.75	0.75	0.35	2.13	28.83
1	4	5	3.500	0.395	3.50	1.00	0.43	2.32	11.29
1	5	5	2.500	0.354	2.50	0.75	0.50	1.49	14.14
1	6	5	4.300	0.209	4.50	0.50	0.28	1.78	4.86
1	7	5	1.700	0.597	1.75	1.50	0.46	3.23	35.11
1	8	5	4.200	0.209	4.75	0.50	0.30	1.64	4.98
1	9	5	0.900	0.379	0.75	1.00	0.34	2.92	42.13
1	10	5	1.700	0.411	1.50	1.00	0.46	2.16	24.16
1	11	5	3.400	0.454	3.50	1.25	0.44	2.81	13.36
1	12	5	1.400	0.487	1.50	1.25	0.43	2.92	34.81
1	13	5	2.650	0.335	3.00	0.75	0.50	1.50	12.66
1	14	5	3.350	0.335	3.75	0.75	0.45	1.67	10.01
1	15	5	1.300	0.481	1.25	1.25	0.41	3.02	36.99
1	16	5	4.000	0.250	4.25	0.50	0.35	1.44	6.25
1	17	5	3.400	0.285	3.75	0.75	0.44	1.69	8.38
1	18	5	2.850	0.576	3.00	1.50	0.49	3.05	20.19
1	19	5	1.350	0.627	1.50	1.25	0.42	2.97	46.48
1	20	5	3.750	0.250	4.00	0.50	0.39	1.27	6.67
1	21	5	2.150	0.518	2.00	1.25	0.50	2.52	24.11
1	22	5	1.800	0.597	1.50	1.50	0.47	3.17	33.16
1	23	5	0.750	0.433	0.75	1.00	0.31	3.22	57.74
1	24	5	4.200	0.112	4.50	0.25	0.30	0.82	2.66
1	25	5	2.900	0.652	3.00	1.50	0.49	3.07	22.48
1	26	5	0.450	0.326	0.50	0.75	0.24	3.16	72.44
1	27	5	0.950	0.371	1.00	1.00	0.35	2.84	39.03
1	28	5	2.850	0.487	3.25	1.00	0.49	2.03	17.10
1	29	5	4.400	0.224	4.75	0.50	0.26	1.95	5.08
1	30	5	0.350	0.137	0.50	0.25	0.21	1.19	39.12
1	31	5	2.800	0.326	3.25	0.75	0.49	1.52	11.64
1	32	5	2.200	0.597	1.75	1.50	0.50	3.02	27.13

SUMMARY ACROSS READINGS

TEST	RDR.	N	M	S
1	A	32	2.414	1.310
1	B	32	2.102	1.267
1	C	32	2.742	1.283
1	D	32	2.539	1.038
1	E	32	2.242	1.340
1	SG	32	2.508	1.361

TABLE 9. STATISTICAL ANALYSIS OF TEST 2 DATA

SUMMARY ACROSS READERS

TEST	RDG.	N	M	S	SG	W	SE	W/SE	CV
2	1	5	4.100	0.379	4.50	0.75	0.33	2.30	9.25
2	2	5	4.300	0.411	4.50	1.00	0.28	3.56	9.55
2	3	5	0.800	0.447	0.75	1.00	0.32	3.11	55.90
2	4	5	4.250	0.500	4.25	1.25	0.29	4.27	11.76
2	5	5	1.950	0.326	1.75	0.75	0.48	1.55	16.72
2	6	5	4.250	0.177	4.50	0.50	0.29	1.71	4.16
2	7	5	4.000	0.468	4.50	1.25	0.35	3.60	11.69
2	8	5	3.700	0.447	4.25	1.00	0.40	2.49	12.09
2	9	5	3.100	0.454	3.75	1.25	0.48	2.63	14.65
2	10	5	1.800	0.326	1.75	0.75	0.47	1.58	18.11
2	11	5	0.650	0.224	0.50	0.50	0.29	1.74	34.40
2	12	5	4.250	0.250	4.50	0.50	0.29	1.71	5.88
2	13	5	3.150	0.379	3.50	1.00	0.47	2.12	12.04
2	14	5	3.100	0.379	3.50	1.00	0.48	2.10	12.23
2	15	5	2.750	0.750	2.75	1.75	0.50	3.52	27.27
2	16	5	2.350	0.576	2.50	1.50	0.50	2.99	24.49
2	17	5	1.650	0.335	1.50	0.75	0.46	1.63	20.33
2	18	5	2.150	0.335	2.25	0.75	0.50	1.51	15.60
2	19	5	3.850	0.652	4.50	1.75	0.38	4.66	16.93
2	20	5	4.850	0.137	5.00	0.25	0.13	1.95	2.82
2	21	5	0.600	0.137	0.50	0.25	0.28	0.91	22.82
2	22	5	2.400	0.652	3.25	1.50	0.50	2.99	27.16
2	23	5	3.350	0.675	3.75	1.50	0.45	3.33	20.16
2	24	5	2.350	0.518	2.50	1.25	0.50	2.49	22.06
2	25	5	1.500	0.354	1.25	0.75	0.44	1.70	23.57

SUMMARY ACROSS READINGS

TEST	RDR.	N	M	S
2	A	25	2.920	1.290
2	B	25	2.440	1.213
2	C	25	3.130	1.227
2	D	25	2.840	1.237
2	F	25	2.910	1.482
2	SG	25	3.050	1.434

TABLE 10. STATISTICAL ANALYSIS OF TEST 3 DATA

SUMMARY ACROSS READERS

TEST	RDG.	N	M	S	SG	W	SE	W/SE	CV
3	1	6	4.083	0.258	4.00	0.75	0.33	2.28	6.32
3	2	6	3.750	0.224	3.50	0.50	0.39	1.27	5.96
3	3	6	3.000	0.354	3.00	1.00	0.48	2.07	11.79
3	4	6	1.833	0.861	1.50	2.00	0.48	4.20	46.97
3	5	6	5.000	0.000	5.00	0.00	0.08	0.00	0.00
3	6	6	0.583	0.129	0.50	0.25	0.27	0.92	22.13
3	7	6	0.583	0.129	0.50	0.25	0.27	0.92	22.13
3	8	6	2.542	0.579	1.75	1.50	0.50	2.99	22.79
3	9	6	3.083	0.408	2.50	1.00	0.48	2.10	13.24
3	10	6	3.708	0.401	4.00	1.25	0.40	3.12	10.80
3	11	6	2.208	0.781	1.75	2.25	0.50	4.52	35.38
3	12	6	0.167	0.204	0.25	0.50	0.16	3.18	122.47
3	13	6	2.333	0.540	1.75	1.50	0.50	2.99	23.15
3	14	6	4.083	0.129	4.00	0.25	0.33	0.76	3.16
3	15	6	1.667	0.665	1.00	1.75	0.46	3.80	39.87
3	16	6	2.417	0.438	1.75	1.00	0.50	1.99	18.12
3	17	6	1.542	0.697	1.00	1.75	0.45	3.92	45.19
3	18	6	3.417	0.438	3.25	1.25	0.44	2.83	12.81
3	19	6	3.000	0.354	2.50	1.00	0.48	2.07	11.79
3	20	6	3.208	0.401	3.25	1.00	0.47	2.15	12.48
3	21	6	1.208	0.641	0.75	1.50	0.40	3.76	53.02
3	22	6	2.542	0.485	1.75	1.25	0.50	2.49	19.09
3	23	6	0.667	0.342	0.50	1.00	0.29	3.44	51.23
3	24	6	4.417	0.258	4.50	0.75	0.25	2.98	5.85
3	25	6	1.917	0.626	1.50	1.50	0.48	3.11	32.65
3	26	6	3.375	0.262	3.25	0.75	0.45	1.68	7.77
3	27	6	0.792	0.368	0.75	0.75	0.32	2.35	46.48
3	28	6	0.250	0.158	0.25	0.50	0.18	2.75	63.25
3	29	6	1.000	0.524	0.50	1.25	0.36	3.45	52.44
3	30	6	2.583	0.492	2.25	1.25	0.50	2.50	19.03
3	31	6	1.833	0.585	1.25	1.50	0.48	3.15	31.88
3	32	6	3.750	0.224	3.50	0.50	0.39	1.27	5.96

SUMMARY ACROSS READINGS

TEST	RDR.	N	M	S
3	A	32	2.219	1.492
3	B	32	2.688	1.324
3	C	32	2.578	1.290
3	D	32	2.352	1.226
3	E	32	2.039	1.480
3	G	32	2.477	1.310
3	SG	32	2.109	1.382

TABLE 11. STATISTICAL ANALYSIS OF TEST 4 DATA

SUMMARY ACROSS READERS

TEST	RDG.	N	M	S	W	CV
4	6	7	0.857	0.349	0.75	40.75
4	9	7	0.964	0.225	0.75	23.33
4	10	7	0.929	0.345	1.00	37.16
4	11	7	1.036	0.094	0.25	9.12
4	12	7	1.321	0.278	0.75	21.05
4	13	7	1.607	0.244	0.75	15.18
4	14	7	1.429	0.238	0.75	16.65
4	15	7	0.821	0.313	0.75	38.15
4	20	7	0.821	0.313	0.75	38.15
4	24	7	1.036	0.304	1.00	29.33
4	25	7	1.464	0.225	0.50	15.36
4	26	7	1.679	0.278	0.75	16.57
4	27	7	1.571	0.345	0.75	21.96
4	28	7	0.964	0.366	1.00	37.95
4	29	7	1.286	0.173	0.50	13.42
4	30	7	1.286	0.225	0.75	17.49
4	34	7	0.786	0.267	0.50	34.02
4	35	7	0.786	0.267	0.50	34.02
4	36	7	0.929	0.313	0.75	33.75
4	37	7	0.857	0.244	0.50	28.46
4	38	7	0.929	0.189	0.50	20.35
4	39	7	0.929	0.189	0.50	20.35
4	40	7	1.071	0.122	0.25	11.39
4	41	7	1.143	0.134	0.25	11.69
4	42	7	1.250	0.204	0.50	16.33
4	43	7	1.179	0.189	0.50	16.03
4	44	7	1.143	0.134	0.25	11.69
4	45	7	1.143	0.197	0.50	17.21
4	46	7	1.429	0.122	0.25	8.54
4	47	7	0.893	0.283	0.75	31.75
4	48	7	0.857	0.244	0.50	28.46
4	54	7	0.929	0.189	0.50	20.35
4	57	7	0.786	0.267	0.50	34.02
4	58	7	1.250	0.144	0.50	11.55
4	59	7	0.964	0.225	0.75	23.33

SUMMARY ACROSS READINGS

TEST	RDR.	N	M	S
4	A	35	1.064	0.455
4	B	35	1.150	0.212
4	C	35	0.943	0.374
4	D	35	1.107	0.194
4	E	35	1.086	0.353
4	F	35	1.043	0.386
4	G	35	1.271	0.253

TABLE 12. STATISTICAL ANALYSIS OF TEST 5 DATA

SUMMARY ACROSS READERS

TEST	RDG.	N	M	S	W	CV
5	1	7	2.643	0.430	1.00	16.25
5	2	7	2.393	0.244	0.75	10.20
5	3	7	2.214	0.267	0.50	12.07
5	4	7	2.071	0.238	0.75	11.48
5	5	7	2.000	0.250	0.75	12.50
5	6	7	2.000	0.250	0.75	12.50
5	7	7	1.893	0.134	0.25	7.06
5	8	7	1.643	0.197	0.50	11.97
5	9	7	1.464	0.173	0.50	11.78
5	10	7	1.214	0.173	0.50	14.21
5	11	7	0.964	0.336	0.75	34.88
5	12	7	1.036	0.267	0.75	25.80
5	13	7	0.857	0.244	0.50	28.46
5	16	7	1.679	0.374	1.00	22.28
5	17	7	1.464	0.488	1.50	33.32
5	18	7	1.179	0.624	1.75	52.98
5	19	7	1.571	0.374	1.25	23.80
5	20	7	1.536	0.173	0.50	11.23
5	21	7	1.286	0.267	0.75	20.79
5	22	7	1.143	0.197	0.50	17.21
5	23	7	1.071	0.278	0.75	25.96
5	24	7	1.036	0.267	0.75	25.80
5	25	7	1.214	0.304	0.75	25.01
5	26	7	1.107	0.349	1.00	31.55
5	27	7	0.964	0.366	1.00	37.95
5	28	7	0.821	0.313	0.75	38.15
5	31	7	1.107	0.349	1.00	31.55
5	38	7	0.893	0.405	1.00	45.31
5	43	7	1.393	0.518	1.50	37.16
5	44	7	1.179	0.374	1.00	31.73
5	56	7	0.821	0.313	0.75	38.15
5	59	7	0.821	0.313	0.75	38.15

SUMMARY ACROSS READINGS

TEST	RDR.	N	M	S
5	A	32	1.422	0.722
5	B	32	1.570	0.432
5	C	32	1.234	0.561
5	D	32	1.578	0.339
5	E	32	1.352	0.748
5	F	32	1.391	0.553
5	G	32	1.227	0.477

TABLE 13 STATISTICAL ANALYSIS OF TEST 6 DATA

SUMMARY ACROSS READERS

TEST	RDG.	N	M	S	W	CV
6	1	6	1.667	0.408	1.25	24.49
6	2	6	1.542	0.431	1.25	27.93
6	3	6	1.708	0.459	1.25	26.85
6	4	6	1.792	0.401	1.00	22.35
6	5	7	2.071	0.313	0.75	15.13
6	6	7	2.071	0.374	1.00	18.06
6	7	7	2.035	0.419	1.00	20.58
6	8	7	2.071	0.472	1.25	22.81
6	9	7	2.143	0.537	1.25	25.07
6	10	7	2.107	0.518	1.25	24.56
6	11	7	2.107	0.476	1.25	22.57
6	12	7	2.071	0.572	1.50	27.62
6	13	7	2.036	0.443	1.25	21.77
6	14	7	2.071	0.450	1.25	21.72
6	15	7	2.214	0.466	1.25	21.05
6	16	7	2.786	0.770	2.25	27.63
6	17	7	3.321	0.826	2.50	24.86
6	18	7	3.357	0.705	2.00	21.00
6	19	7	3.393	0.497	1.50	14.65
6	20	7	3.321	0.345	0.75	10.39
6	21	7	2.964	0.585	1.50	19.74
6	22	7	2.929	0.494	1.50	16.87
6	23	7	3.036	0.585	1.50	19.27
6	24	7	3.000	0.595	1.50	19.84
6	25	7	2.893	0.518	1.50	17.89
6	26	7	2.929	0.554	1.75	18.91
6	27	7	3.000	0.520	1.50	17.35
6	28	7	2.929	0.515	1.50	17.57
6	29	7	2.821	0.494	1.25	17.51
6	30	7	2.893	0.593	1.50	20.49
6	31	7	2.857	0.659	2.00	23.07
6	32	7	3.107	0.775	2.00	24.95
6	33	7	2.750	0.595	1.75	21.64
6	34	7	2.500	0.433	1.25	17.32
6	35	7	2.821	0.345	1.00	12.23
6	36	7	3.179	0.590	1.50	18.56
6	37	7	3.464	0.603	1.75	17.39
6	38	7	3.500	0.433	1.25	12.37
6	39	7	3.429	0.401	1.25	11.69
6	40	7	3.250	0.323	1.00	9.93
6	41	7	2.929	0.703	2.00	24.00
6	42	7	2.536	0.783	2.25	30.88
6	43	7	3.321	0.590	1.50	17.77
6	44	7	3.357	0.497	1.50	14.80
6	45	7	3.143	0.593	1.75	18.86
6	46	7	3.000	0.540	1.50	18.00
6	47	7	2.821	0.374	1.00	13.26
6	48	7	2.857	0.537	1.75	18.81
6	49	7	3.429	0.535	1.25	15.59
6	50	7	3.500	0.433	1.25	12.37
6	51	7	3.464	0.393	1.00	11.36
6	52	7	3.393	0.318	0.75	9.38
6	53	7	3.286	0.304	0.75	9.24
6	54	7	3.107	0.453	1.00	14.58
6	55	7	2.607	0.283	0.75	10.87
6	56	7	2.429	0.313	1.00	12.90
6	57	7	2.357	0.244	0.75	10.35
6	58	7	2.321	0.345	1.00	14.86
6	59	7	2.214	0.366	1.00	16.53
6	60	7	2.286	0.366	1.00	16.01

SUMMARY ACROSS READINGS

TEST	RDR.	N	M	S
6	A	60	3.054	0.890
6	B	60	2.433	0.614
6	C	60	2.412	0.365
6	D	60	2.650	0.747
6	E	60	3.192	0.674
6	F	56	2.973	0.436
6	G	60	2.563	0.707

The statistical data in Tables 8 and 9 (Tests 1 and 2) are used to determine the reproducibility of the Test Method. The 57 pairs of values of the means, M, and standard deviations, S, are plotted as points of a scattergram shown in Figure 8. The data appear to follow a quadratic function with low variation at the extreme ends of the Ringelmann number range, and higher variations toward the center. This relationship seems reasonable in that smoke readings near either end of the Ringelmann number scale intuitively would appear to be easier to estimate by an observer than readings near the middle of the scale. A least squares regression equation of the form $\hat{S} = a + bm + cm^2$ was fitted to the data points in Figure 8 by the method of weighted least squares. Weights were assigned to the data points in order to compensate for the violation of two assumptions of the statistical method. First, the coordinates of the data points are averages, which are not always computed from the same number of observations, and second, the variances along the regression curve are not equal. The appropriate weighting formula is $W = f/(\alpha + \beta m + \gamma m^2)^2$, where W represents the weight*, f denotes the number of degrees of freedom associated with the computed standard deviation $\hat{S}$; α, β, γ denote constant terms in the true regression curve; and m is the mean concentration. The parameters α, β, and γ are not known, nor are their least squares estimates, a, b and c. An iterative approach is required, using successive estimates of a, b, c, and W which converge to a least squares solution. By this procedure, the equation $\hat{S} = 0.1 + 0.3M - 0.07M^2$ is obtained as an estimate of the true regression curve $S = \alpha + \beta m + \gamma m^2$. The weighted standard deviation of the residuals about the regression curve is found to be 0.11. This curve summarizes the results of the reproducibility analysis and represents the best estimate of the reproducibility of the Test Method based on data obtained in this study.

The calculated regression equation was used to provide estimates of S for each value of M in Tables 8 through 10. The ratio of the range to the estimated standard deviation, w/SE, may be compared with the 99 percent point of the Studentized range to check the quality of the test data. Only reading period 19 of Test 2 was found to contain data which would normally be considered outlying. However, due to the subjective nature of the smoke reading measurement, it is felt that this measurement should not be excluded from the statistical analyses.

* In calculating weights, estimated variances less than 0.01 were set at 0.01 to prevent the weights from becoming excessively large.

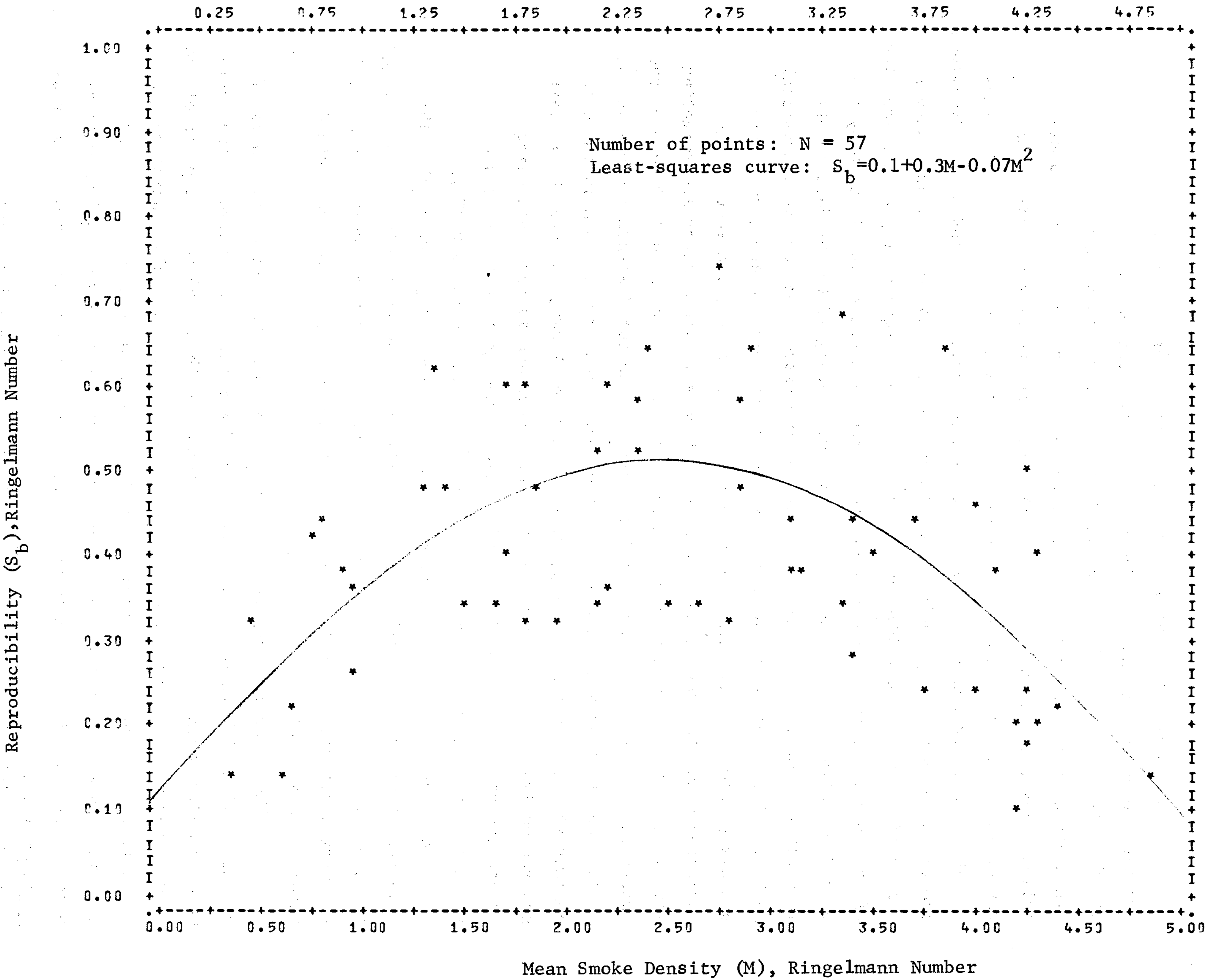


FIGURE 8. SCATTER DIAGRAM AND LEAST SQUARES CURVE RELATING REPRODUCIBILITY (BETWEEN -OBSERVER STANDARD DEVIATION) TO MEAN SMOKE DENSITY

In developing the reproducibility analysis relationship shown in Figure 8, only the data from the smoke generator tests were considered. Since these data represent simulated smoke reading conditions a natural concern is whether the reproducibility relationship holds in actual smoke reading situations. An analysis was performed to check the validity of applying the reproducibility data determined from the smoke generator tests to actual source emissions as encountered in Tests 4, 5, and 6.

The regression curve estimating the standard deviation of the observer estimates as a function of the mean reading was used to calculate the standard deviations of the readings collected in the field for tests 4, 5, and 6 (data in Tables 4, 5, and 6). The procedure followed was to calculate the mean of the smoke density estimates for each reading period in Tables 4, 5, and 6, across observers. Only those reading periods where all seven observers responded were used. These mean readings were then substituted into the reproducibility relationship to obtain an estimated standard deviation. This estimated standard deviation was then compared to the actual standard deviation of the seven reader estimates for the reading period. The method used for this comparison is presented by Hoel[12]. The test statistic used was:

$$t = \frac{n\,S^2}{\sigma^2} \quad ,$$

where n = 7, the number of observer smoke density estimates per reading period, S^2 is the square of the standard deviation calculated for the seven reader estimates, and σ^2 is the estimated variance of the readings, i.e., the square of the standard deviation estimated from the reproducibility relationship. Assuming the readings follow a normal distribution, the test statistic, t, will have a Chi-squared distribution with n-1 degrees of freedom. The hypothesis being tested is that the variance, σ^2, as estimated by the reproducibility relationship is the same as the variance of the readings collected in the field. The results of the tests of significance conducted at the 95 percent confidence level are shown in Table 14.

TABLE 14. COMPARISON OF GENERATOR-DERIVED REPRODUCIBILITY CURVE WITH SOURCE DATA

Test-Source	Number of Reading Periods Tested	Number of Reading Periods in which the Estimated Standard Deviation was Significantly Different from Calculated Standard Deviation	
		−	+
4. Boiler Stack	35	0	8
5. Coke Plant Stack	32	1	7
6. Steel Plant Stack	56	5	1
Total	123	6	16

Out of the 123 cases, about 82 percent yield results which indicate that the standard deviation calculated from the reproducibility relationship was not significantly different from that calculated directly for the observer data. In general, the fact that the reproducibility relationship was derived solely from the smoke generator test data does not appear to significantly limit its use in considering reproducibility variation for data collected in the field.

Analysis of Accuracy

The data in Tables 1 and 2 provide a basis for estimating the accuracy of the observer readings as well as the reproducibility measure. Each observer estimate can be compared to the "standard value" as recorded on the smoke generator transmissometer. The histogram in Figure 9, based upon 285 measurements, summarizes the percent differences for all seven observers over Tests 1 and 2. The percent differences were calculated using the equation,

$$\text{Percent Difference} = \frac{(\text{Observers Estimate}) - (\text{Smoke Generator Reading})}{\text{Smoke Generator Reading}} \times 100.$$

The distribution has a mean of -1.84 percent, which suggests a slight negative bias, and a standard deviation of 26.26 percent. The hypothesis that the true bias is zero versus the alternative two-sided hypothesis that the true bias is different from zero is tested by use of Student's t as follows:

$$t = \bar{x}\sqrt{n}/s = (-1.84)\sqrt{285}/26.26 = -1.18 \quad .$$

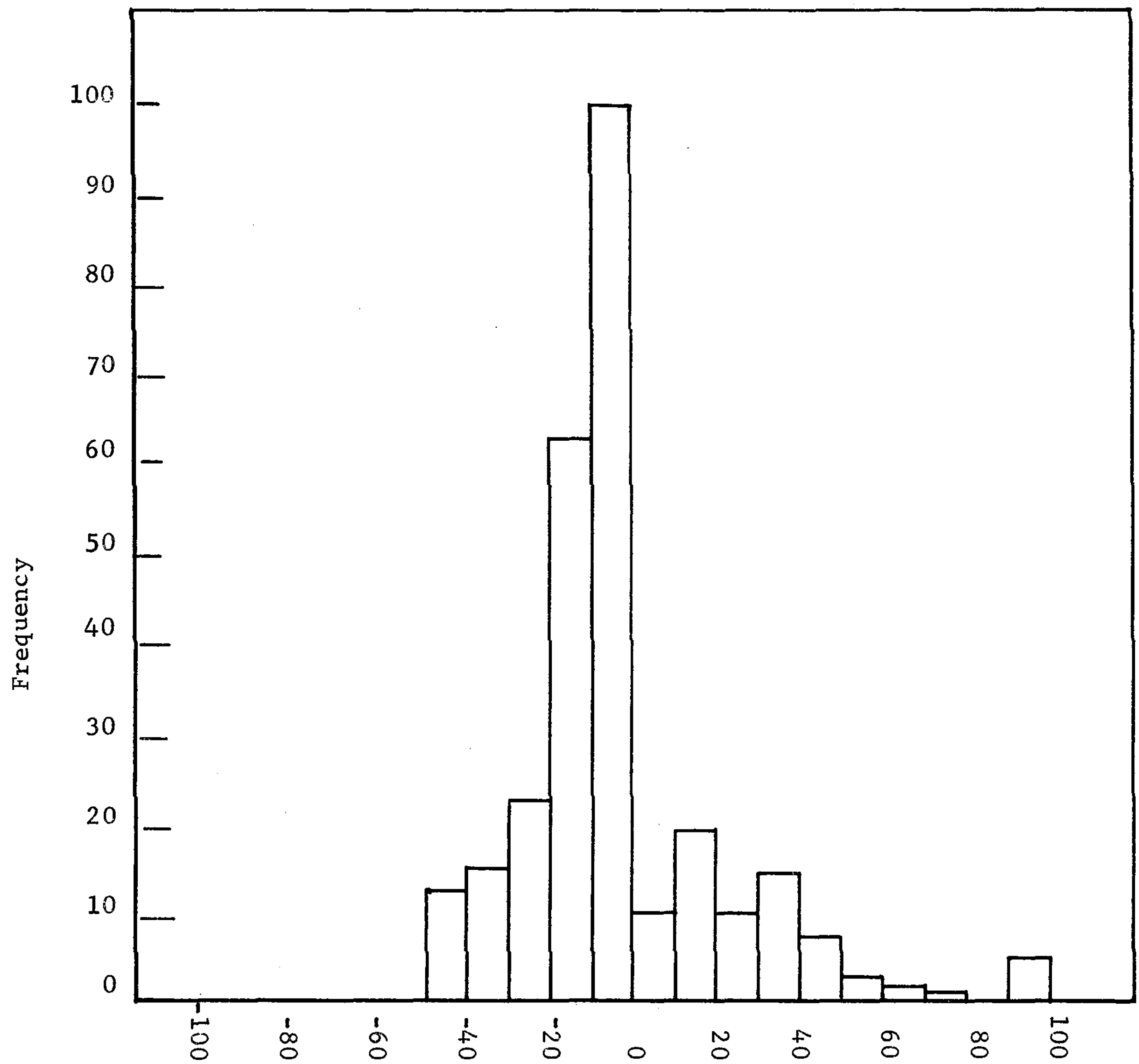


FIGURE 9. HISTOGRAM OF DIFFERENCES IN SMOKE DENSITY ESTIMATES AND SMOKE GENERATOR READINGS FOR ALL OBSERVERS (TESTS 1 AND 2)

For n-1 =284 degrees of freedom, the value of t is not statistically significant at the 99 percent level. Therefore, the test hypothesis is not rejected and it is concluded that the true bias is probably zero.

Table 15 presents a summary of the accuracy analysis of ASTM Method D 3211. The table shows for each observer, n, the number of observations; $\bar{x}$, the mean percent difference between the observer estimates and the smoke generator transmissometer readings; s, the standard deviation of the percentage differences between the observer and smoke generator readings; and t, the statistical test value to determine if the bias is significantly different than zero. The last column gives the conclusion drawn from the application of Student's test. The results show that the bias in estimates of four observers probably are significant.

Table 16 presents a summary of the accuracy of observer estimates of smoke density across the Ringelmann range 1/2 to 5. The table shows for 1/4 Ringelmann number increments the mean percent difference of the observer estimates and the generator reading, the standard deviation of the differences in the observer-generator readings, Students' t statistic calculated as described previously, and the conclusion of the significance test. For example, the mean of all observer estimates at Ringelmann 2.00 (based on the generator reading) was 7.5 percent higher than the generator reading. The standard deviation of the observer-generator differences is 25.92. Students' t statistic applied at the 99 percent significance level that the bias of readings at Ringelmann 2 is probably zero.

In general, the mean of observer estimates are higher than the generator values on the lower end of Ringelmann range and lower than the generator value on the upper end. However, a significant bias was not detected except at a few levels at higher Ringelmann numbers (above 3 1/4). Overall the bias of -1.84 is shown to be indistinguishable from zero by Student's t statistic.

As an overall measure of accuracy, the mean of most observer estimates at readings across the Ringelmann range are within about 10 percentage points of the generator values.

TABLE 15. SUMMARY OF ACCURACY ANALYSIS OF ASTM METHOD D 3211 (RINGELMANN METHOD)

Observer	n, No. of Observations	$\bar{x}$, Mean Percent Difference	s, Std. Dev. of Percent Difference	Student's t	Conclusion[a]
A	57	-3.39	21.08	-1.21	NS
B	57	-18.40	16.18	-8.52	S
C	57	12.33	23.08	4.03	S
D	57	10.26	36.23	2.14	NS
E	32	-13.63	18.11	-4.26	S
F	25	-5.96	9.41	-3.17	S
Total	285	-1.84	26.26	-1.18	NS

(a) NS = t is not statistically significant at the 99 percent level and the test hypothesis that the true bias is zero is not rejected.

S = t is statistically significant at the 99 percent level, the test hypothesis is rejected, and it is concluded that the true bias is probably not zero.

TABLE 16. SUMMARY OF ACCURACY ANALYSIS OF OBSERVER ESTIMATES AS A FUNCTION OF SMOKE DENSITY

Generator Smoke Density, Ringelmann No.	Number of Observations	Mean Percent Difference	Standard Deviation	Student's t	Conclusion[a]
0.50	20	2.50	47.23	0.24	NS
0.75	20	13.33	48.85	1.22	NS
1.00	5	-5.00	37.08	-0.30	NS
1.25	10	12.00	32.93	1.15	NS
1.50	25	5.33	32.89	0.81	NS
1.75	25	8.57	27.04	1.58	NS
2.00	5	7.50	25.92	0.65	NS
2.25	10	-3.33	14.86	-0.71	NS
2.50	15	-4.00	18.44	-0.84	NS
2.75	6	0.00	27.27	0.00	NS
3.00	15	-6.67	17.02	-1.52	NS
3.25	15	-17.44	15.78	-4.28	S
3.50	20	-6.07	11.65	-2.33	NS
3.75	20	-12.00	11.77	-4.56	S
4.00	5	-6.25	6.25	-2.24	NS
4.25	15	-6.27	10.54	-2.30	NS
4.50	39	-6.84	6.56	-6.51	S
4.75	10	-9.48	4.84	-6.19	S
5.00	5	-3.00	2.74	-2.45	NS
Total	285	-1.84	26.26	-1.18	NS

(a) NS = t is not statistically significant at the 99 percent level and the test hypothesis that the true bias is zero is not rejected.

S = t is statistically significant at the 99 percent level, the test hypothesis is rejected, and it is concluded that the true bias is probably not zero.

DISCUSSION AND CONCLUSIONS

The interlaboratory study provides the following quantitative measures of the precision and accuracy of ASTM Method D 3211 for determining the relative density of black smoke.

(1) The reproducibility, S_b, of single smoke density estimates over the Ringelmann number range of 0 to 5 is described by the equation:

$$S_b = 0.1 + 0.3\ M - 0.07\ M^2,$$

where S_b and M, the mean observer smoke density, are expressed in Ringelmann number. A comparison shows that reproducibility calculated from the preceding equation is characteristic of the variability inherent in smoke density readings of both generator-produced and actual source smoke emissions.

(2) The average results obtained in the smoke generator tests show that observer estimates of smoke density were lower than the smoke generator transmissometer readings by about two percentage points. The observer generator difference is statistically indistinguishable from zero therefore, it can be concluded that the method is not biased. The accuracy of observer smoke density estimates is shown to be within about 10 percentage points of the generator value over the entire Ringelmann range.

The tests to determine the precision and accuracy of procedure were performed on the same day under nearly ideal weather conditions. As a result, these data probably represent a "best estimate" of the precision and accuracy of the Test Method for the group of observers that participated in the test. The occupations, experience, and smoke reading frequency of the participants appear to represent a cross section of the smoke observer population.

The reproducibility data generated in this study provide a quantitative basis to assess the certainty with which violations of visible emission standards can be detected. These regulations usually state that visible emissions may not exceed a specified level, typically 1 to 2 Ringelmann number, for more than specified time periods in 1 hour and in 24 hours. When a smoke observer makes a series of smoke density readings for regulatory purposes, the accuracy and precision of the readings must be considered if a violation is to be declared with certainty. For example, if an observer estimates a reading of Ringelmann 2, the true or actual smoke density is probably in a range which includes values which are both above and below 2, due to variability in the test method. Suppose that the violation level is set at Ringelmann 2. Since there is a possibility that the actual smoke density may be less than 2, a clear violation can not be established. The question then arises "what observer readings confirm a violation with certainty or high probability"? If we assume that the results obtained in this study are representative of the smoke observer population, the reproducibility data can provide an answer to this question.

In Table 17, the reproducibility obtained from the least-squares curve is presented for various levels of smoke density. If a violation is specified at a certain smoke density level, we can use this reproducibility data to calculate the probability that a reader will detect a violation, or the percentage of all smoke readers that would record a violation. These percentages are shown in Table 17 for various smoke densities which might be specified as the violation levels. The table shows, for example, if the violation level is specified to be a Ringelmann number of 1.50, 85 percent of the readers would detect a violation when the actual smoke emission was 2.0. Equivalently, we could say that the probability is 85 percent that a reader would declare a violation when the smoke density was 2.0 Ringelmann number, where a violation was defined as a Ringelmann number greater than 1.50.

Suppose the reader is taking readings for a certain time interval and he is to indicate the smoke readings that exceed a specified smoke density level. If he detects three readings in the interval which exceed 1.50, the probability that the smoke emission exceeds a specified level for various situations can be calculated. If three readings are Ringelmann 2, the probability of detecting these three high readings is $(.85)^3 = 0.61$.

As the number of occurrences of smoke level in excess of 2.0 increase, the reader's probability of detecting the smoke levels above 1.5 increases. For the preceding example, Table 18 shows the probability of detecting 3 readings or more which are greater than 1.50, as a function of the actual number of readings in excess of 2.00. These data may be applied to any time interval.

TABLE 17. PROBABILITY OF DECLARING SMOKE READINGS ABOVE SPECIFIED LEVEL BASED ON REPRODUCIBILITY DATA

Actual Smoke Density[(a)]	Reproducibility, between reader standard deviation[(a)]	Percent Probability of Declaring a Reading to Exceed the Specified Ringelmann Number Limit of:			
		1.50	2.00	2.50	3.00
0.00	0.11	0.0	0.0	0.0	0.0
0.25	0.18	0.0	0.0	0.0	0.0
0.50	0.25	0.0	0.0	0.0	0.0
0.75	0.31	0.8	0.0	0.0	0.0
1.00	0.36	8.4	0.3	0.0	0.0
1.25	0.41	26.8	3.2	0.1	0.0
1.50	0.44	50.0	12.9	1.2	0.0
1.75	0.47	70.2	29.8	5.5	0.4
2.00	0.49	84.6	50.0	15.4	2.0
2.25	0.50	93.3	69.2	30.8	6.7
2.50	0.50	97.7	84.1	50.0	15.9
2.75	0.50	99.4	93.4	69.2	30.9
3.00	0.48	99.9	98.1	85.1	50.0
3.25	0.46	100.0	99.7	94.8	70.5
3.50	0.43	100.0	100.0	99.0	87.7
3.75	0.39	100.0	100.0	100.0	97.2
4.00	0.35	100.0	100.0	100.0	99.8

(a) In Ringelmann number

TABLE 18. PROBABILITY OF DETECTING MULTIPLE READINGS IN EXCESS OF A SPECIFIED LEVEL

Number of Times the Smoke Level Exceeds 2	Percent Probability of Detecting 3 or More Readings in Excess of 1.50
3	61
4	89
5	97
10 or more	100

In addition to the quantitative measures, the test results also permit some qualitative observations about the Test Method. The significant difference between the results of Tests 1 and 2 and Test 3 emphasizes the subjective nature of the Test Method. One explanation is that some observers evidently felt after viewing plumes of known density that they were underestimating the Ringelmann readings. As a result, they compensated and, in several cases thereafter, significantly overestimated the smoke densities. Eye fatigue has been suggested by one of the participants as the explanation for the deterioration in observer accuracy. Both of these situations might occur with observers who do not perform smoke density estimates on a regular basis. The phenomenon stresses the need for regular certification and application of the Test Method to maintain observer confidence and proficiency.

The tests were conducted with observer-to-stack distances ranging from 21 to 2500 meters. The results do not show any significant difference in reproducibility of the measurements, however some decrease in accuracy might be expected with increasing stack-to-observer distance. The accuracy was determined only at 21 meters.

The comparison of smoke density readings of generator and actual source emission show no significant difference in reproducibility of the readings. While this supports application of generator-derived data to field application, it also would appear to be a testimony for the validity of using a smoke generator for training and certification of smoke observers.

RECOMMENDATIONS

The following recommendations are offered for improvement of performance and interpretation of the results of the ASTM Method D 3211-73T.

(1) The precision and accuracy data obtained in this study should be included in the description of the Test Method along with an explanation of its applicability to smoke reading results.

(2) The recertification period should be reduced to 3 to 6 months, to develop and maintain observer proficiency.

(3) Accuracy of the Test Method should be studied as a function of observer-to-stack distance.

(4) Paragraph 8.1 should be amended to include "trained eye" for smoke observations.

(5) Section 6 implies that in performance of the Test Method, smoke readings should be made every 15 to 30 seconds over a one hour period. Due to eye fatigue, observers could not be expected to make valid estimates over this period. A more realistic reading procedure should be adopted.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of Mr. Walter V. Cropper, Manager-Special Projects, ASTM, throughout the course of the Threshold Program.

Mr. R. E. Heffelfinger and Mr. R. E. Poling of Battelle's Columbus Laboratories are acknowledged for their assistance in the conduct of the smoke reading tests.

Our appreciation is extended to Dr. Peter Warner and Mr. Sam Nimlin of Wayne County (Michigan) Department of Health for their cooperation and the use of the smoke generator facility and to Mr. Lee Jager, Michigan Department of Natural Resources and Mr. Arthur Hockstra, Erie County (Pennsylvania) Health Department for their cooperation in this study.

Lastly, we wish to acknowledge and express our sincere appreciation to the following individuals and organizations who cooperated in the conduct of this test program.

Samual Gibbs	Wayne County (Michigan) Department of Health Air Pollution Control Division
Tom McCollough	George D. Clayton and Associates
James McReynolds	TRW, Research Resources, Inc.
Milo Smith	Michigan Department of Natural Resources Division of Air Pollution Control
James Tibbitts	Erie County (Pennsylvania) Health Department
Bernard Wagar	Wayne County (Michigan) Department of Health Air Pollution Control Division
Denny Wagoner	Research Triangle Institute

REFERENCES

1. Foster, J. F. and Beatty, G. H., "Interlaboratory Cooperative Study of the Precision and Accuracy of the Measurement of Nitrogen Dioxide Content in the Atmosphere using ASTM Method D 1607", ASTM Report No. 22. 1607, September 4, 1973.

2. Foster, J. F. and Beatty, G. H., "Interlaboratory Cooperative Study of the Precision and Accuracy of the Measurement of Sulfur Dioxide Content in the Atmosphere using ASTM Method D 2914, ASTM Report No. 22. 2914, September 4, 1973.

3. Foster, J. F., Beatty, G. H., and Howes, J. E., Jr., "Interlaboratory Cooperative Study of the Precision and Accuracy of the Measurements of Total Sulfation in the Atmosphere using ASTM Method D 2010", ASTM Report No. 22. 2010.

4. Foster, J. F., Beatty, G. H., and Howes, J. E., Jr., "Interlaboratory Cooperative Study of the Precision of Measurements of Particulate Matter in the Atmosphere (Optical Density of Filtered Deposit) using ASTM Method D 1704" ASTM Report No. 22. 1704.

5. Foster, J. F., Beatty, G. H., and Howes, J. E., Jr., "Interlaboratory Cooperative Study of the Precision and Accuracy of Measurements of Dustfall using ASTM Method D 1739", ASTM Report No. 22. 1739.

6. Annual Book of ASTM Standards, Part 23, American Society of Testing Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103.

7. Instrument Manufactured by Mine Safety Appliances Company, or equivalent thereof.

8. Manufactured by Environmental Industries, Raleigh, North Carolina 27608.

9. Mandel, J., "Repeatability and Reproducibility", Materials Research and Standards, 11, No. 8, 8-16 (Aug., 1971).

10. "Tentative Recommended Practice for Statements on Precision and Accuracy", ASTM Method D 2906.

11. "Use of the Terms Precision and Accuracy as Applied to Measurement of a Property of a Material", ASTM Method E 177.

12. Hoel, P. G., Introduction to Mathematical Statistics, Second Edition, John Wiley and Sons, Inc. New York, N. Y., Pg. 219 (1958).

13. Natrella, M. G., Experimental Statistics, National Bureau of Standards Handbook 91, Table A-10 (1963).

APPENDIX

REPRINT OF ASTM

STANDARD METHOD OF TEST FOR RELATIVE DENSITY OF BLACK SMOKE (RINGELMANN METHOD)

ASTM Designation: D 3211 - 73 T

Designation: D 3211 - 73 T

Standard Method of Test for

RELATIVE DENSITY OF BLACK SMOKE (RINGELMANN METHOD)[1]

This Tentative Method has been approved by the sponsoring committee and accepted by the Society in accordance with established procedures, for use pending adoption as standard. Suggestions for revisions should be addressed to the Society at 1916 Race St., Philadelphia, Pa. 19103.

1. Scope

1.1 This method covers the determination of the relative density of black smoke.

1.2 The apparent darkness or opacity, or both, of a stack plume depends upon the following:

1.2.1 The concentration of particulate matter in the effluent,

1.2.2 The size of the particulate,

1.2.3 The depth of the plume being viewed,

1.2.4 Natural lighting conditions, such as the direction of the sun relative to the observer, and the amount of light,

1.2.5 The color of the particulates, and

1.2.6 The background conditions.

1.3 In the determination of visual emissions, the Ringelmann Smoke numbers are considered a special case for measuring shades of black or gray of fly ash arising from combustion processes.

2. Summary of Method

2.1 The Ringelmann Smoke Chart, indicating shades of gray (blend of black and white) by which the density of smoke rising from stacks may be compared, is used to determine the density of the black smoke. A qualified observer may use the Ringelmann Chart, or other aids to make this determination.

3. Significance

3.1 The Ringelmann Chart was originally intended as a guide for plant operators in adjusting furnaces to burn coal efficiently. Since the emission of soot is an inherently preventable act of pollution, it was then adopted by many jurisdictions as a basis of air pollution control regulations. Despite its subjective nature, it has been found useful in precisely this context. In addition, Ringelmann readings tend to correlate closely with adverse public reaction to the sight of a discharge of black smoke, and probably less well with the potential of that smoke to degrade visibility. Ringelmann readings are a subjective test, and may or may not be a direct measure of the quantity of emission.

4. Interferences

4.1 Errors or variations in Ringelmann reading may occur due to the following conditions:

4.1.1 Variations in the background against which the smoke is viewed,

4.1.2 Variations in the ambient light which illuminates the Ringelmann charts and which may be considerably different from the light in the area of the stack,

4.1.3 The optical focus of the observer's eyes when looking from the smoke to the charts or data sheets, or both, and

4.1.4 Changes in the type of fuel burned and variations in the fuel result in different smoke density emissions due to water vapor, particulate size, shape, and color.

5. Apparatus

5.1 Ringelmann Smoke Chart,[2] which employs a scheme whereby graduated shades of gray, varying by five equal steps between white

[1] This method is under the jurisdiction of ASTM Committee D-22 on Sampling and Analysis of Atmospheres.

Current edition approved March 29, 1973. Published July 1973.

[2] Described in U. S. Department of Interior Bureau of Mines Information Circular 8333 issued May 1967.

and black are employed to evaluate the density of smoke emissions.

5.1.1 Ringelmann Smoke Chart shall be produced by preparing a rectangular grid of carbon-black lines of definite width and spacing on a flat-white background of paper or cardboard having a reflectance equivalency of reagent grade magnesium oxide (MgO) powder or barium sulfate ($BaSO_4$) powder.

Cards 154.5 mm wide by 224.5 mm long shall be prepared as follows:

Card 0 All white, percent black 0.

Fig. 1 Card 1 Black lines 1 mm wide, 10 mm apart, leaving white spaces 9 mm square, with 6.75 mm white border, percent black 20.

Fig. 2 Card 2 Black lines 2.3 mm wide, 10 mm apart, leaving white spaces 6.3 mm square, with 5.4 mm white border, percent black 40.

Fig. 3 Card 3 Black lines 3.7 mm wide, 10 mm apart, leaving white spaces 6.3 mm square, with 5.4 mm white border, percent black 60.

Fig. 4 Card 4 Black lines 5.5 mm wide, 10 mm apart, leaving white spaces 4.5 mm square, with 4.5 mm white border, percent black 80.

Card 5 All black, percent black 100.

5.2 *Micro-Ringelmann Smoke Chart*[3] (Fig. 5)—a direct facsimile reduction of the standard Ringelmann Smoke Chart employs the same scheme as the Ringelmann but the smaller scale permits easier handling.

5.3 *Smoke Scope*[4], which incorporates a viewing apparatus to compare the smoke being observed to a reference film. Light from an area adjacent to the smoke being observed is transmitted through the reference film onto a mirror, and then through a lens onto a second mirror. From this second mirror, the reference image can be compared with the smoke being observed. The reference film is located exactly at the local distance of the virtual image; therefore the image can be compared to the smoke being observed without refocusing of the observer's eye.

6. Calibration and Standardization

6.1 *Qualification of Observer*—Any qualified observer must complete a smoke-reading course with a content approved by or conforming to the course presented by EPA (Air Pollution Office (APO).[5] Upon completion of the course, any qualified observer must be certified by the agency or a recognized organization giving the course. To pass the test for certification, an observer must be able to assign Ringelmann numbers (to the nearest 0.25 Ringelmann number) to 25 different smoke plumes, with an error not to exceed 15% on any one reading and an average error not to exceed 7.5% on all 25 readings. All qualified observers must pass this test every year in order to remain certified.

6.2 The smoke generator used to train the observers must have the capabilities to produce gray/black smoke from 0 to No. 4 Ringelmann. A calibrated smoke indicator or light transmission meter located in the source stack of the smoke generator shall be used for the actual determination of the related Ringelmann emission readings.

7. Procedure

7.1 *General:*

7.1.1 Glance at the stack every 15 to 30 s using the observer's own trained eyes or using the aid of a Ringelmann chart, micro-Ringelmann, or smoke scope, and record the data as stated in Section 8 and using the recommended data forms. Ringelmann numbers correspond to the following densities of smoke:

Ringelmann Number	Percent Light Transmission through Smoke	Smoke Density, %
0	100	0
1	80	20
2	60	40
3	40	60
4	20	80
5	0	100

7.1.2 Record the Ringelmann number to the nearest ¼ fraction of a whole Ringelmann number that the observer is capable of reading. Record the conditions under which the reading is being taken. Under adverse conditions, such as noted in Section 4 or when the observer must deviate from the procedures listed, the observer shall use whole Ringelmann number readings.

7.1.3 In determination of the smoke emissions, readings should be taken over a relatively long period of time, for example, 1 h, or if the process is a batch-type operation, then readings should be made over at least one complete cycle.

7.2 *Use of The Ringelmann Smoke Chart:*

7.2.1 Support the chart on a level with the

---

[3] Published by McGraw-Hill Publishing Co.

[4] Manufactured by the Mine Safety Appliances Co., or the equivalent thereof.

[5] EPA training course is offered by the Institute for Air Pollution Training, Office of Manpower Development.

observer's eye, in line with the smoke plume being observed, and at such a distance (about 50 ft from the observer) that the lines on the chart merge into shades of gray. Glance from the smoke plume to the chart, and determine the Ringelmann number that most nearly corresponds with the shade of the smoke being observed.

7.2.2 Observe the smoke at approximately right angles to the direction of plume travel, with the sun behind the observer as much as possible. Observe the smoke at the point of exit from the stack, except for detached plumes (which shall be observed at the point of greatest density) and plumes containing steam (which shall be observed just beyond the point of steam dissipation).

7.2.3 Observe the smoke against a contrasting background (usually the blue sky), and with enough light present so that the plume can be adequately seen. Where air pollution control regulations permit nighttime observations, use back lighting. The observer must be trained and certified for nighttime readings before reporting such readings.

7.2.4 Stand at least two stack heights away from the stack being observed, and not more than 2500 ft (762 m) from the stack.

7.3 *Use of the Micro-Ringelmann Smoke Chart:*

7.3.1 Support the chart on a level with the observer's eye, in line with the smoke plume being observed, at approximately, an arm's length from the observer or at a distance that the lines on the chart merge into shades of gray. View the smoke plume through the slot in the middle of the chart, and determine the Ringelmann number that most nearly corresponds with the shade of smoke being observed.

7.3.2 See 7.2.2 to 7.2.4.

7.4 *Use of the Smoke Scope*

7.4.1 View the plume through the instrument, aiming it so that smoke fills the field of vision through the aperture. Compare the reference images to the smoke plume being observed, and determine the Ringelmann number that most nearly corresponds with the shade of smoke being observed.

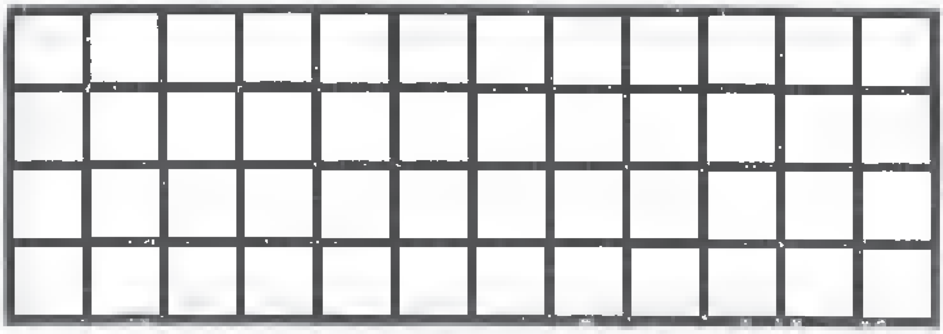
7.4.2 See 7.2.2 to 7.2.4.

8. Calculation and Report

8.1 *Determination of Average Smoke Density*—Observe the smoke density, using the Ringelmann Smoke Chart, the Micro-Ringelmann Smoke Chart, or the smoke scope, at constant intervals of 15 or 30 s. At the end of the observation period, divide the sum of the Ringelmann numbers by the total number of observations made. The results shall be the average smoke density, expressed as a Ringelmann number.

8.2 *Percentage Smoke Density*—Any smoke density expressed as a Ringelmann number can be converted to a percentage smoke density by multiplying the Ringelmann number by 20. Thus, a Ringelmann Number 1 would equal a 20% density, and a Ringelmann Number 5 (black smoke) would equal a 100% density.

8.3 *Suggested Data Form*—A convenient form for recording and computing the average percentage of smoke density, as well as the average Ringelmann, over a time period of 1 h is shown in Fig. 6.



FIGS. 1 thru 4 Ringlemanns Scale for Grading the Density of Smoke[4]
FIG. 1 Equivalent to 20 Percent Black

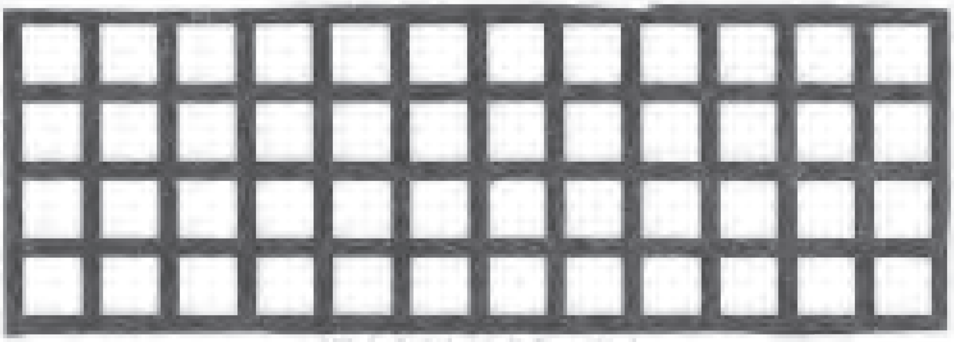


FIG. 2 Equivalent to 40 Percent Black

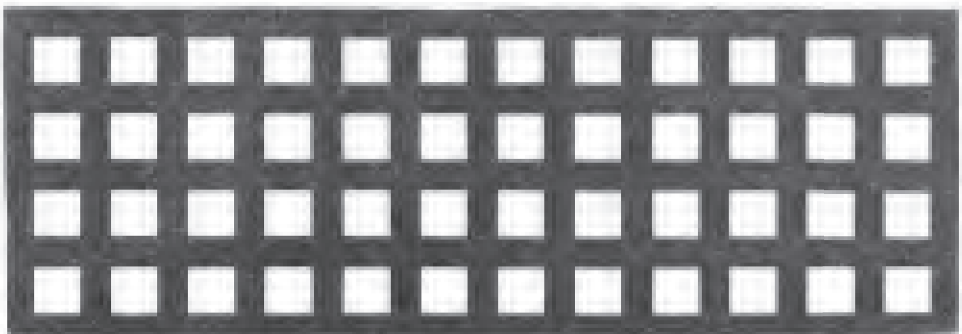


FIG. 3 Equivalent to 60 Percent Black

[4] A print for the Ringelmann's Scale for Grading the Density of Smoke is available from ASTM Headquarters, 1916 Race St., Philadelphia, Pa. 19103. Request adjunct No 12-432100-00.

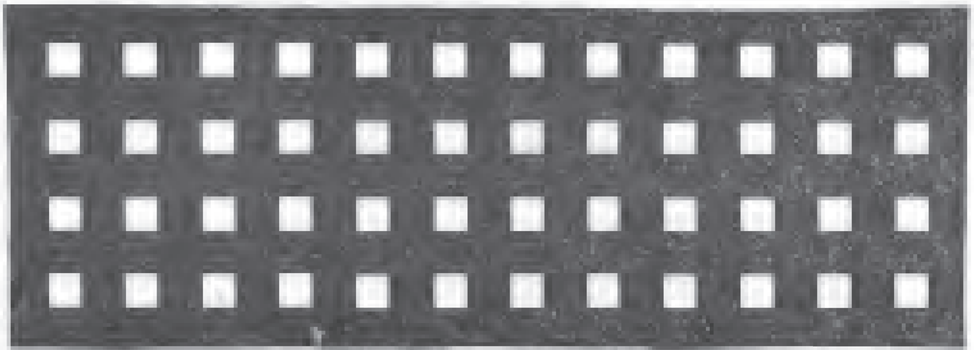


FIG. 4 Equivalent to 80 Percent Black

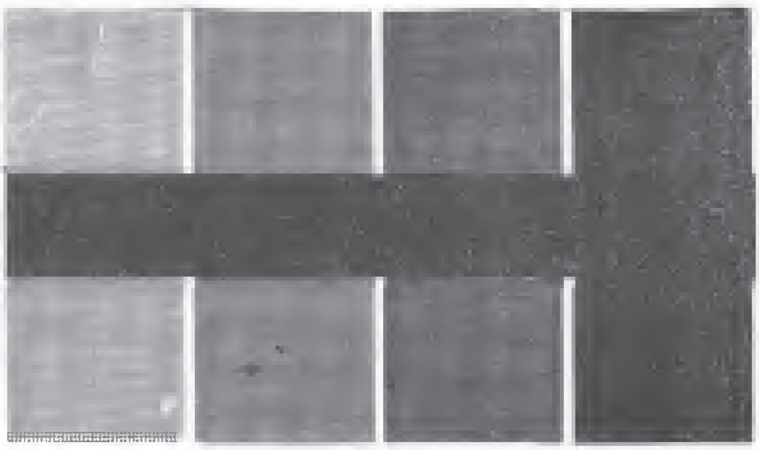
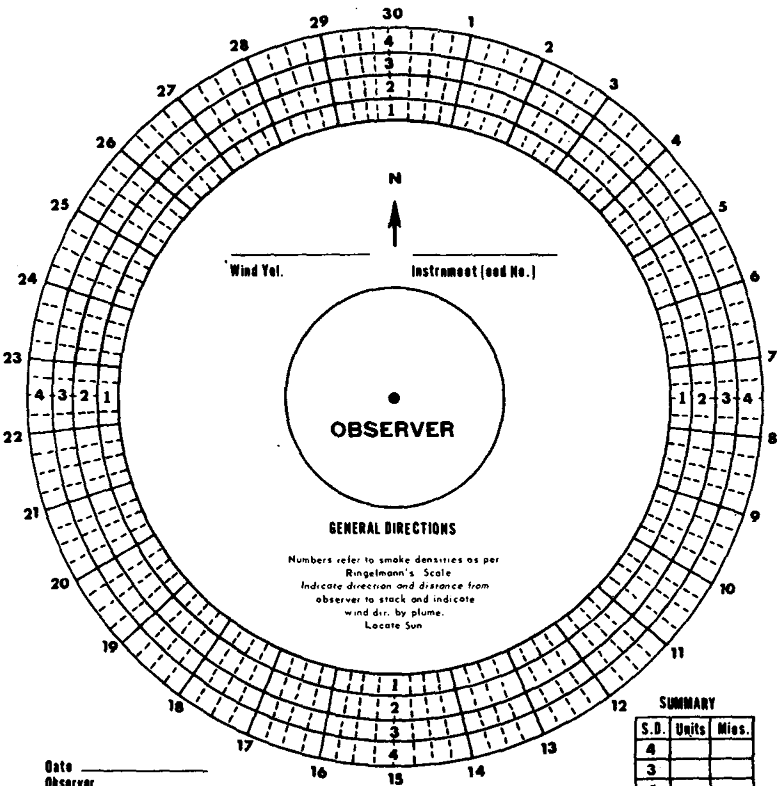


FIG. 5 Micro-Ringelmann Smoke Chart

SMOKE OBSERVATION FORM



SUMMARY

S.D.	Units	Mins.
4		
3		
2		
1		
TOTAL		

Date ____________

Observer ____________

Hours from ______ to ______

NAME ____________

LOCATION ____________

STACK DESCRIPTION ____________

____

FIG. 6 Smoke Observation Form